Analytical Modeling of the Delta East Side Tributaries

A Deliverable
For
State Water Project Contractors Authority
and
Metropolitan Water District of Southern California

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ABSTRACT

Analytical modeling of the Delta east side tributaries was performed to determine the sources of turbidity and organic carbon to Delta drinking water intakes under present watershed and climatic conditions (2000 through 2010). Turbidity and organic carbon are two pollutants of primary concern to Delta water resource managers. Drinking water intakes in the Delta are most effectively managed with knowledge of the timing and quantity of turbidity and organic carbon flux to the Delta from upstream sources. An existing Watershed Analysis Risk Management Framework (WARMF) model of the Sacramento River Watershed was extended geographically to include the region between Morrison Creek and the Stanislaus River. This region includes the Cosumnes, Mokelumne, and Calaveras Rivers, Dry Creek, Bear Creek, French Camp Slough, and local drainage areas on the east side of the Sacramento-San Joaquin River Delta. Data were collected from 1921-2007 to drive the model and evaluate its calibration. The simulation was calibrated for flow, turbidity, and organic carbon. The calibrated model successfully predicted each parameter for various regions of the study area with pollutant sources reflecting combinations of upstream inflows, natural nonpoint source load, agricultural areas, and urban areas. It was determined that upstream inflows and nonpoint source loads were the major sources of these water quality constituents in the Delta east side tributaries region. The calibrated model is suitable for use in evaluating future watershed management practices and performing short-term forecasts to determine flow and pollutant loading to the Delta from the east side tributaries.

1 MODEL SETUP

Introduction

Background

The Sacramento-San Joaquin River Delta is a major source of drinking water for districts serving northern and southern California. The Delta receives inflows from the Sacramento River and San Joaquin River, as well as several smaller tributaries including the Calaveras, Cosumnes, and Mokelumne Rivers. Ocean water, transported through the Carquinez Straits on the incoming tide also mixes with the inland freshwater sources. Therefore, the water quality at the Delta drinking water intakes is dependent upon the pollutant loading from each of these sources and complex pathways by which these pollutants move through the Delta to drinking water intakes.

Stakeholders which use water from the Sacramento - San Joaquin River Delta have a critical interest in the Delta's water quality, as water filtration and chemical treatment process costs are directly related to the quality of incoming waters. Additionally, the seasonal presence of an endangered fish species has been correlated with Delta water quality and can affect hydrosystems facility management. Turbidity and dissolved organic carbon (DOC) concentration are of particular interest to water resource managers.

Delta smelt, which was listed in 1993 as threatened under both the California Endangered Species Act (CESA) and Federal Endangered Species Act (FESA), spawn in river channels and backwaters of the Sacramento and San Joaquin River systems. Delta Smelt begin their upstream spawning migration from Suisun Bay in late fall or early winter. This migration is believed to be correlated with the turbidity of Delta channels. Therefore, the risk of entraining Delta Smelt in drinking water intakes is greatly increased when high turbidity conditions exist in the vicinity of State Water Project facilities during the winter months when Delta Smelt are present.

As indicated in USEPA's Stage 1 Disinfectants and Disinfection Byproducts (D/DBP) Rule (USEPA 1998), "EPA continues to believe that the Stage 1 DBPR [Disinfectants and Disinfection Byproducts Rule] is necessary for the protection of public health from exposure to potentially harmful DBPs." USEPA also recognizes the connection between TOC levels in source water and the protection of public health (USEPA 2001). In order to ensure adequate protection of human health, USEPA requires drinking water utilities "to remove specified percentages of organic material (measured as total organic carbon) [from the source of the water supply, i.e., plant influent] that may react with disinfectants to form DBPs. With lower precursor concentrations, lower levels of DBPs will be formed.

Efficient management of Delta water resources requires knowledge of the source, magnitude and timing of chemical constituent fluxes to the Delta. Assessment of the contribution of the various sources to organic carbon and turbidity concentrations at the intakes is best accomplished through numerical modeling.

Modeling Objective

Delta water managers require technical information to cost-effectively operate Delta pumping facilities and identify significant sources of organic carbon to the Delta. Pollutants at drinking water intakes originate from a combination of urban, industrial, agricultural, and natural sources. To develop effective water resource management policy, the sources of pollutants and the timing of pollutant loads must be quantified to determine the impact at drinking water intakes.

The application of WARMF documented in this report fills a critical gap in previous modeling initiatives. Existing WARMF models of the Sacramento and San Joaquin Rivers calculate the concentration and loading of chemical and physical constituents to the Delta from their respective watersheds. There is a gap between them, however, so the loading to the Delta from its east side tributaries (e.g. Cosumnes, Mokelumne and Calaveras Rivers) is not currently included in the analytical models. Preliminary indication from previous Delta modeling indicates that these tributaries may be an important source of pollutants. Additionally, WARMF models constructed prior to this project did not simulate turbidity. Therefore, the existing Sacramento WARMF model was extended geographically and analytically to address these deficiencies.

Specifically, the objectives of the current project include:

1. Extend the geographic extent of the Sacramento WARMF model to include the Delta east side tributaries between Morrison Creek and the Stanislaus River.

2. Populate the Delta east side tributary region of the WARMF model with soil, land use, meteorology, rain chemistry, air quality, reservoir releases, water diversion, irrigation, point source discharge, gage flow, and water quality monitoring data.

3. Perform hydrologic calibration to minimize differences between simulated and observed flow data.

4. Add the capability to simulate turbidity to the existing WARMF model algorithms.

5. Perform a water quality calibration suitable for simulating the major sources of turbidity and organic carbon pollutant loading and in-stream water quality. Although all major water quality parameters will be simulated including temperature, nutrients, major cations and anions, dissolved oxygen, suspended sediment etc., the calibration will be focused on those water quality parameters of greatest concern: turbidity, total suspended sediment and organic carbon.

6. Compile and present WARMF time series output for stream discharge, turbidity and organic carbon. Time series output will be compiled for each of the locations where WARMF models of the Sacramento, east side tributaries, and San Joaquin watersheds interface with the Delta DSM2 model. These locations include: Sacramento River at I-Street Bridge, Yolo Bypass, San Joaquin River at Vernalis, Mokelumne and Cosumnes Rivers at their confluence, Calaveras River, and local Delta drainage (areas contributing flow directly to the delta).

Model Domain

In 2003, CALFED funded a project for monitoring and investigations of the San Joaquin River and its tributaries. As part of this project, the WARMF watershed model was applied to the San Joaquin River to trace pollutants from their source to their sink at the Stockton Deep Water Shipping Channel. In 2008, a separate WARMF was set up to simulate the Sacramento River and its watershed that extends from the confluence with Morrison Creek upstream to Shasta Lake. In 2010, the Sacramento model domain was extended to include the Putah Creek watershed as part of a separate project funded by the Central Valley Salinity Coalition. The current project, funded by the State Water Project Contractors Authority and Metropolitan Water District of Southern California, extends the domain further to include the land area located on the east side of the Sacramento-San Joaquin River Delta between Morrison Creek and the Stanislaus River. Major tributaries to the east side of the Delta (referred to in this report as the east side tributaries) include the Cosumnes, Mokelumne, and Calaveras Rivers. With this current addition to the modeling extent, WARMF can now be used to simulate river discharge and pollutant flux from all tributaries to the Sacramento – San Joaquin Delta. Figure 1-1shows the current extent of the Sacramento and San Joaquin modeling infrastructure.

Since the Delta east side region is part of the much larger Sacramento River WARMF project, the “Model Setup” section of this report will include description of the inputs used throughout the entire model domain including the Sacramento River watershed. The “Model Calibration” and “Source Contribution” sections of the report will be confined to the Delta east side tributaries. Detailed information on calibration and simulation in the Sacramento River watershed portion of the model domain is available in a report prepared for the California Urban Water Agencies titled, “Task 3 Technical Memorandum - Analytical Modeling of the Sacramento River” (Systech Water Resources 2011).

Each of the rivers and streams located in the model domain were included from the confluence with the Sacramento River or Delta upstream to either the watershed divide or to one of ten reservoirs, as illustrated in Figure 1-2.

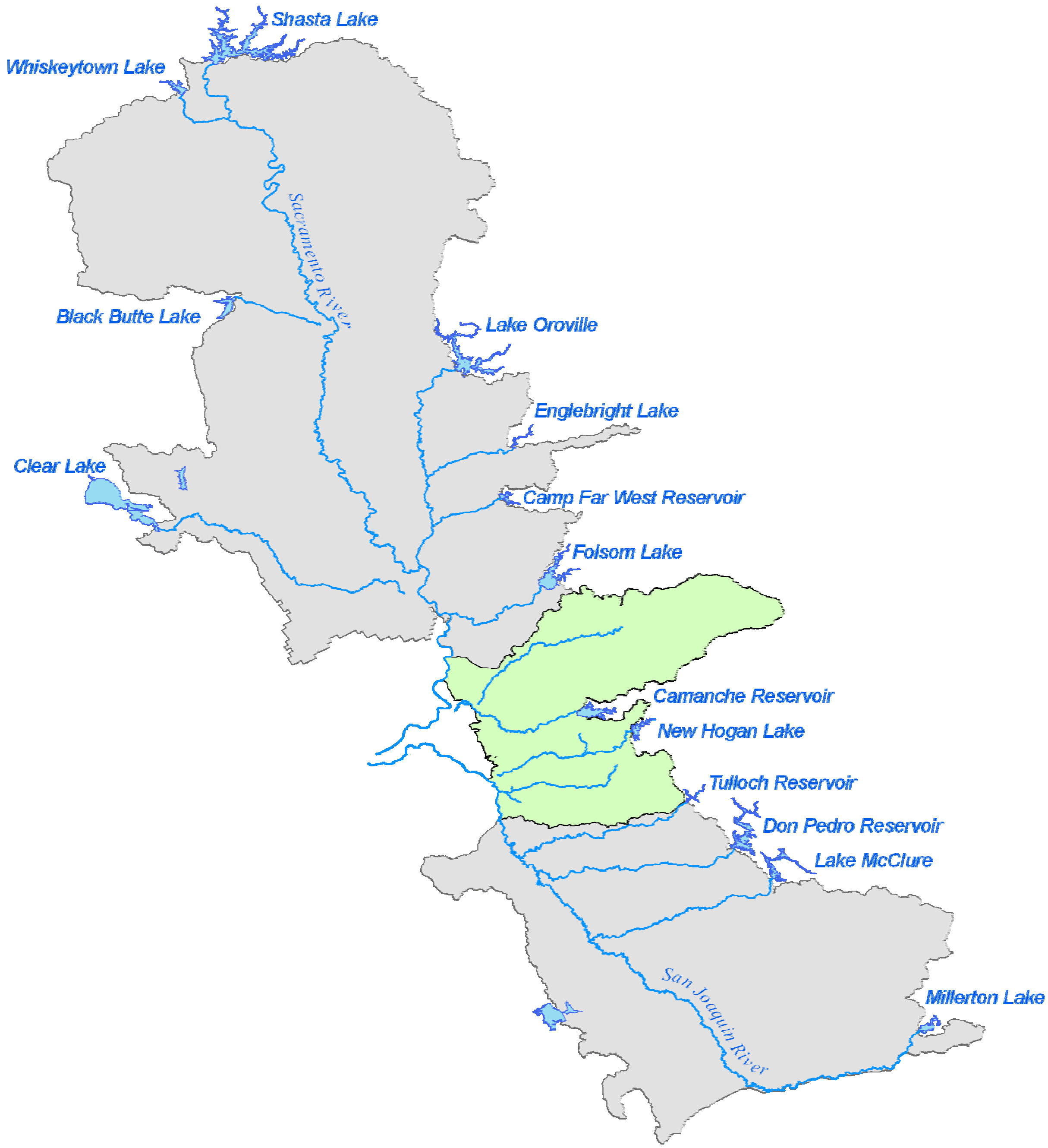

Figure 1-1 The current geographic extent of WARMF modeling capability (area in green corresponds to the extent added to the Sacramento River WARMF model for this project)

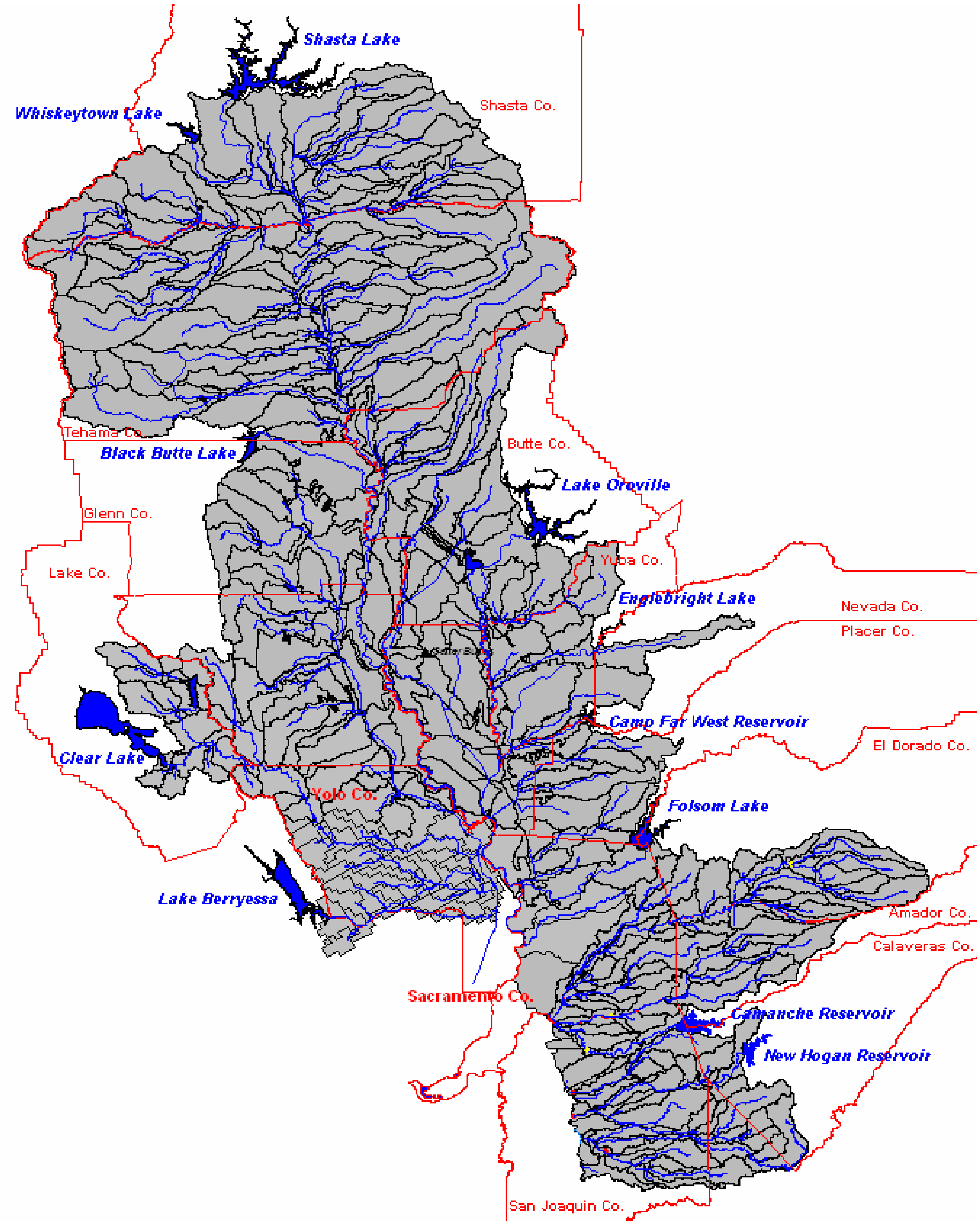

Figure 1-2 The Domain of WARMF Sacramento River Model.

The Sacramento River, its tributaries, and the streams draining directly to the delta defined in Figure 1-2 were divided into 480 river segments and 479 land catchments. Respectively, 116 and 123 of the river segments and land catchments are located within the east side tributaries region of the Sacramento River WARMF model domain. The model simulated natural storm water runoff, irrigation return flow, groundwater table fluctuations within each of the land catchments, and lateral groundwater flow from land catchments to their respective receiving river segments.

With this model set up, the boundary conditions were the Sacramento River at the Shasta Lake Dam, natural watershed divides, and ten reservoirs located on tributaries to the Sacramento River and Delta between Shasta Lake and the Calaveras River. The reservoirs include Lake Oroville, Englebright Lake, Camp Far West Reservoir, and Folsom Lake, on the east side of the Sacramento, Lake Berryessa, Clear Lake, Black Butte Lake, and Whiskeytown Lake on the west side, and Camanche and New Hogan Reservoirs draining delta tributaries. For those boundary conditions, gaging station data provided measured inflows and water quality as inputs to the model. For the agricultural lands, the model inputs included daily diversions, location of water diversions, and areas upon which the irrigation water was applied. Based on the locations of diversions, the model used the water quality of the source water when applying that water as irrigation.

Hydrologic Simulation

WARMF simulates hydrology based on water balance and physics of flow. It begins with precipitation on the land surface. Precipitation and irrigation water can percolate into the soil. Within the soil, water first goes to increase the moisture in each soil layer up to field capacity. Above field capacity, water percolates down to the water table, where it flows laterally out of the land catchment according to Darcy's Law. Water on the soil or within the soil is subject to evapotranspiration, which is calculated based on temperature, humidity, and season. The amount of water entering and leaving each soil layer is tracked. If more water enters the soil than leaves it, the water table rises. If the water table reaches the surface, the soil is saturated and overland flow occurs. The overland flow is calculated by Manning's equation.

Rivers accept the subsurface and overland flow from catchments linked to them. They also receive point source discharges and flow from upstream river segments. Diversion flows are removed from river segments. The remaining water in the river is routed downstream using the kinematic wave algorithm. The channel geometry, Manning's roughness coefficient, and bed slope are used to calculate depth, velocity, and flow. The velocity is a measure of the travel time down the river, which in turn affects the water quality simulation. A thorough description of the processes simulated by WARMF is in the WARMF Technical Documentation (Chen, Herr, and Weintraub 2001).

Water Quality Simulation

The fundamental principle which guides WARMF simulation of water quality is heat and mass balance. Heat enters the soil in water from precipitation and irrigation. Heat is exchanged between catchments and the atmosphere based on the thermal conductivity of the soil. Heat in water leaving the catchments enters river segments, which combine the heat from multiple sources. As in catchments, there is thermal exchange between rivers and the atmosphere based on the difference in temperature between the water and the air. Radiative heating and cooling is also calculated for surface waters. Temperature is then calculated by heat balance throughout the model.

Chemical constituents enter the model domain from atmospheric deposition and from point source discharges. They can also enter the land surface in irrigation water and fertilizer application. Some chemicals are produced by the weathering of minerals in the soil. Chemical species move with water by percolation between soil layers, groundwater lateral flow to rivers, and surface runoff. Each soil layer is considered to be a mixed reactor, as is the land surface within each land use. Within the soil, cations are adsorbed to soil particles through the competitive exchange process. Anions and organic carbon are adsorbed to the soil using an adsorption isotherm. A dynamic equilibrium is maintained between dissolved and adsorbed phases of each ion. Reactions transform the dissolved chemical constituents within the soil. The dissolved oxygen concentration is tracked, and as dissolved oxygen goes to zero, anoxic reactions take place. When overland flow takes place, sediment is eroded from the catchment surface according to the modified universal soil loss equation. The sediment carries adsorbed constituents (e.g. organic carbon) with it to the river.

Rivers accept the water quality which comes with each source of flow. Each river segment is considered a completely mixed reactor. Ions form an equilibrium between dissolved and adsorbed to suspended sediment. Sediment can settle to the river bed and is scoured from the river bed when velocity is greater than critical velocity. Chemical reactions are based on first order kinetics with their rate adjusted with a temperature correction. Algae are represented by three types: greens, blue-greens, and diatoms. Each has their own optimum growth rate, nutrient half-saturation concentrations, light saturation, optimum temperature, and temperature range for growth. At each time step, algal growth is a function of nutrient limitation, light limitation, and temperature limitation. Light penetration is a function of the algae, detritus, and total suspended sediment concentrations. Light intensity is integrated over the depth of the river segment.

Simulated Parameters

By default, WARMF simulates flow, temperature, and many chemical and physical parameters. Including a complete suite of parameters makes it possible to simulate important watershed transport and transformation processes including advection, adsorption equilibrium, settling, resuspension, biological processes, and oxic and anoxic chemical reactions. Salinity was calculated as total dissolved solids (TDS) by summing the concentrations of the major cations and anions. Electrical conductivity (EC) was calculated by multiplying the TDS by 1.50. The ratio was determined through an analysis of concurrently measured TDS and EC in the Sacramento River watershed. Organic carbon was subject to interactions with nutrients, dissolved oxygen, and temperature within the model. The array of hydrologic, chemical, and physical variables simulated in the Sacramento River watershed is shown in Table 1.1. Most parameters were used in model inputs and outputs. Some, like alkalinity and the “total” parameters at the bottom of the list, were only calculated from other parameters.

Table 1.1 Parameters Simulated by WARMF for the Sacramento River Watershed

Parameter	Input	Calculated	Output
Flow	X	X	X
Depth		X	X
Velocity		X	X
Temperature	X	X	X
NOx	X		
SOx	X		
pH		X	X
Ammonia (as N)	X	X	X
Calcium	X	X	X
Magnesium	X	X	X
Potassium	X	X	X
Sodium	X	X	X
Sulfate	X	X	X
Nitrate (as N)	X	X	X
Chloride	X	X	X
Phosphate (as P)	X	X	X
Alkalinity		X	X
Inorganic Carbon	X	X	X
Fecal Coliform	X	X	X
BOD	X	X	X
Dissolved Oxygen	X	X	X
Blue-green Algae	X	X	X
Diatoms	X	X	X
Green Algae	X	X	X
Periphyton	X	X	X
Detritus	X	X	X
Clay	X	X	X
Silt	X	X	X
Sand	X	X	X
Total Suspended Sediment		X	X
Total Phosphorus		X	X
Total Kjeldahl Nitrogen		X	X
Total Nitrogen		X	X
Total Organic Carbon		X	X
Total Phytoplankton		X	X
Total Dissolved Solids (TDS)		X	X
Turbidity		X	X
Electrical Conductivity (EC)		X	X

Three species of algae were included in WARMF. The biomass concentrations of algae species were converted to chlorophyll and summed for total phytoplankton. Sediment was represented by sand, silt, and clay fractions in WARMF. Sand was considered bed load, while silt and clay were part of suspended load. Total Suspended Sediment was the sum of silt and clay. Total Sediment included sand as well.

Simulating Turbidity

Because turbidity is easily measured, there is extensive data used to indicate potential presence of Delta Smelt. Management of water supply pumps in the Delta is constrained by the Delta Smelt to minimize the risk of fish being entrained and killed by the pumps. Turbidity is a measure of light scattering in the water, and therefore is only an indirect measure of physical pollutants. A relationship between turbidity and physical parameters like total suspended sediment, phytoplankton, total organic carbon and detritus can be estimated to ascertain and predict turbidity entering the Delta from its tributaries. A preliminary analysis of measured water quality data collected at Sacramento River at Freeport and San Joaquin River at Vernalis produced the relationship between turbidity and total suspended sediment shown in Figure 1-3. Using these data, the relationship between turbidity and total suspended sediment was found to be linear with an r^2 of 0.75. Regression statistics were also calculated using subsets of the paired TSS and turbidity data. These subsets included combinations of low (<100 NTU) turbidity, high turbidity (>=100 NTU), Vernalis data, Freeport data, entire period of record, and recent years.

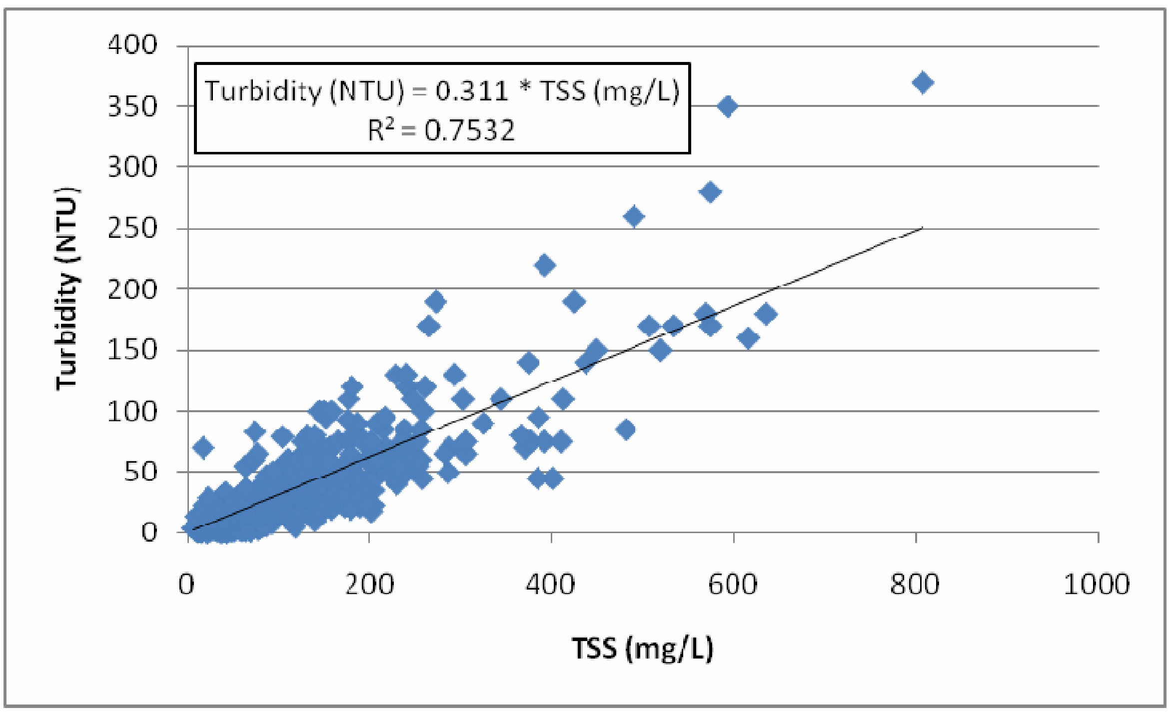

Figure 1-3: Correlation Between Turbidity and Total Suspended Sediment, San Joaquin River at Vernalis and Sacramento River at Freeport data

Figure 1-4 shows the relationship developed using all available turbidity and TSS data collected at the Sacramento River at Freeport. The slope of the equation generated using the Sacramento River data is different than the slope of the equation generated using the combined Vernalis and Freeport data sets, indicating that the relationship between turbidity and TSS is different in the

Sacramento and San Joaquin River systems. The R^2 value for the equation is increased by restricting the data set to samples collected at Freeport.

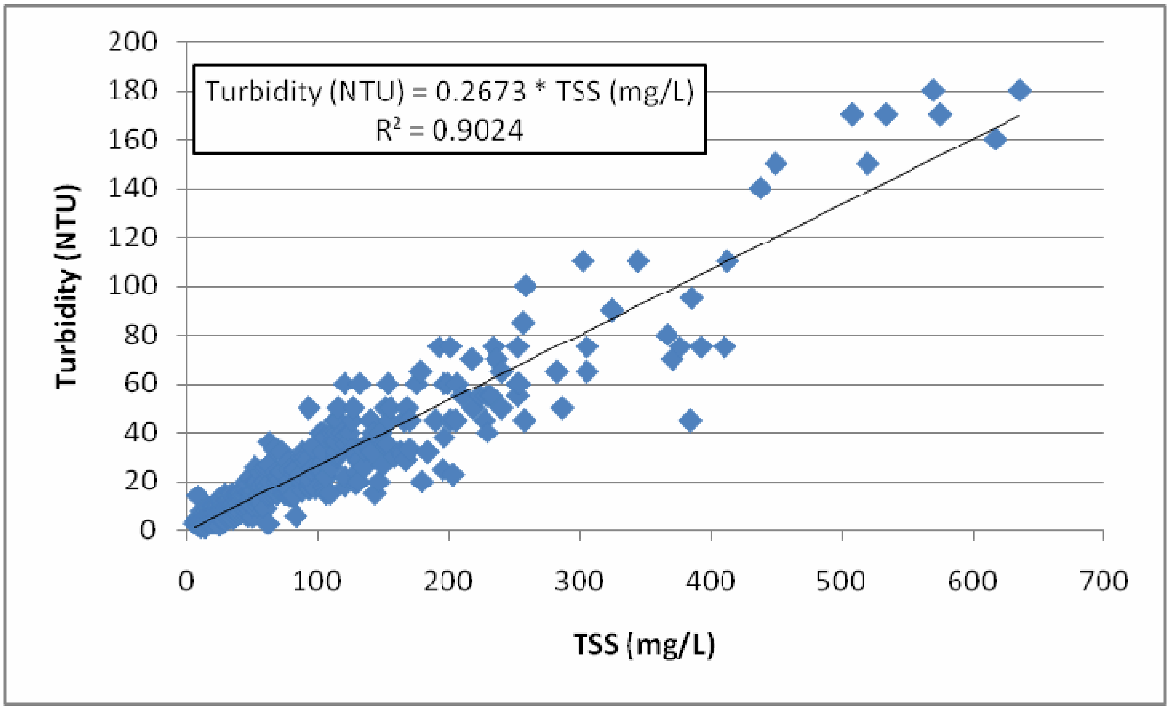

Figure 1-4: Correlation Between Turbidity and Total Suspended Sediment, Sacramento River at Freeport data

Figure 1-5 shows the relationship that was used to simulate turbidity in the Delta east side tributaries. The relationship was developed using data collected between 2008 and 2010 at the Sacramento River at Freeport. While the relationships between turbidity and TSS are very strong, there is some variability between the regression models developed using the different data sets. The variability in the turbidity-TSS relationship is likely due to factors in addition to TSS that affect turbidity measurement. Some of these factors include algae growth, presence of suspended organic matter in the water column, and dissolved constituents that affect the clarity of Sacramento River water. A multivariable analysis with other water quality parameters could produce a stronger predictive equation for turbidity.

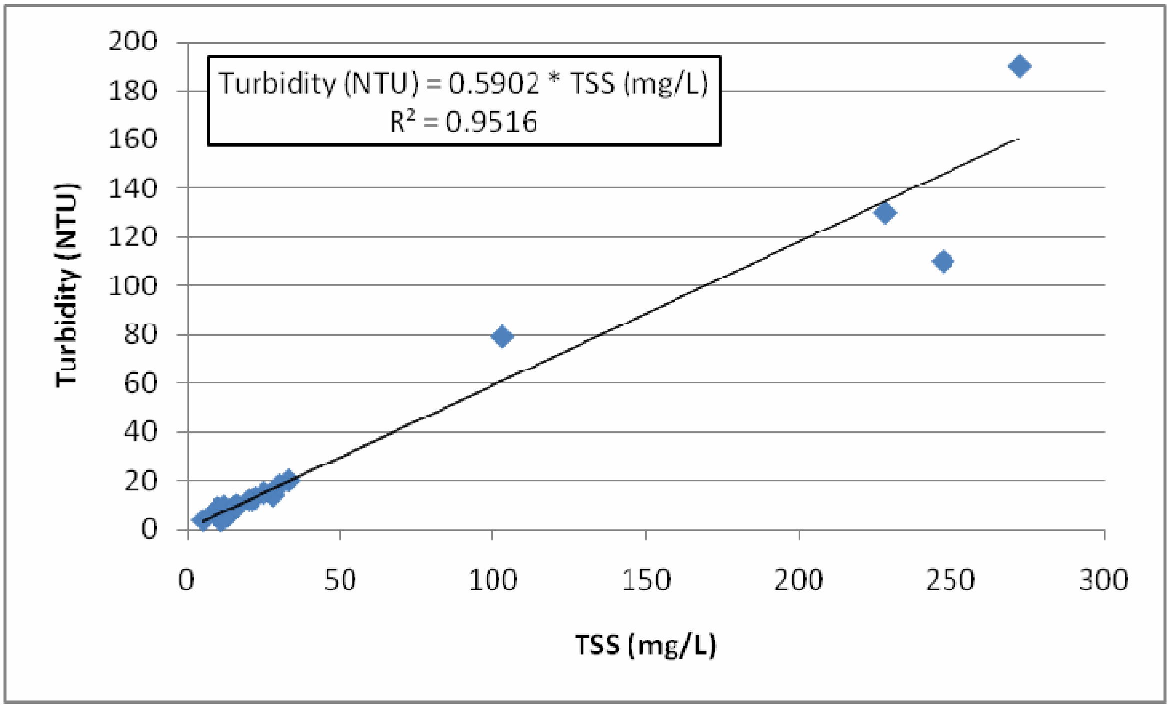

Figure 1-5: Correlation between Turbidity and Total Suspended Sediment, 2008-2009 Sacramento River at Freeport data

Simulating Organic Carbon

Sources of organic carbon that are simulated by WARMF include algal biomass, periphyton, and coarse litter fall. The equations governing the sources of organic carbon include:

Algal Biomass → Dissolved Organic Carbon + Detritus
Periphyton (Grazed and Scoured) → Dissolved Organic Carbon and Detritus
Coarse Litter → Fine Litter → Humus → Organic Carbon

Organic carbon is partitioned between dissolved and adsorbed phases according to adsorption coefficients specified within the WARMF graphical user interface. Organic Carbon concentrations are reduced through the following decay reaction, which takes place in both the soil pore water and in the river segments:

Dissolved Organic Carbon + O_2 → CO_2 + H_2O + NH_4 + SO_4

The rate at which each of these reactions proceeds is regulated by first-order reaction rates that are specified within WARMF. Terrestrial (tree canopy and land surface) and soil column reaction rates are specified in the catchment parameters input dialog, while aqueous reaction rates (water column and river bed) can be adjusted in the river input dialog.

Model Inputs

WARMF is a dynamic watershed model. It requires time series data and model coefficients which describe the physics of the watershed. All of the time series data are derived from measured data. Some of the model coefficients are known from data and thus are not subject to calibration. Other coefficients are only generally known and thus are adjusted to improve the match between model simulation results and measured in-stream flow and water quality data.

The time series used as model inputs are meteorology, air/rain chemistry, boundary inflows, diversions, and point sources. The values of each of these vary daily and drive the model simulations. Categories of time-invariant model coefficients for which information is available include fertilizer application, irrigation water distribution, geometric data (e.g. watershed slope and aspect), and land use. The values of the model coefficients do not change during the course of the simulation. The combination of the time series inputs and model coefficients is used to calculate the amount of water and concentrations of each chemical constituent throughout the watershed for each time step.

The daily values of driving variables are compiled and imported into the Data module of WARMF. During the simulation, the Data module automatically feeds these daily values to the model.

The following sections describe the measured input data for the Sacramento River Model.

Geometric Data

The Digital Elevation Model (DEM) data available from the EPA BASINS web site were imported to WARMF. WARMF used the DEM data to delineate the Sacramento River model domain into land catchments and river segments. WARMF also calculated the geometric dimensions and slope of land catchments and the length and slope of river segments. River segments were further divided manually to spatially align with observed hydrology and water chemistry locations, and to facilitate simulation of specific sub-basins of interest.

Land Use Data

The quantity, timing, and quality of surface water discharge are dependent upon the land use present within the watershed. Each land catchment simulated in the Sacramento River watershed model was assigned various land uses on its surface based on current land use data. The Sacramento River watershed model was originally set up to simulate hydrologic and water quality processes based on the following land use categories: barren, commercial/industrial, confined feeding, coniferous, deciduous, fallow/non-irrigated farm, farm, grassland, marsh, mixed forest, orchard, pasture, residential, rice, scrub/shrub, and water.

Additional land use resolution was added to the model domain as part of the concurrent Sacramento River analytical modeling project sponsored by the California Urban Water Agencies. The current version of the Sacramento WARMF model employs 32 separate classes to describe land use within the model domain. The current land use classes include: Barren Land, Cotton, DairyPA, Deciduous Forest, Double Crop Dairy Land Application, Evergreen Forest, Fallow, Farmsteads, Flowers and nursery, Grassland/Herbaceous, Lagoon, Marsh, Mixed Forest, Native Classes Unsegregated, Olives, citrus & subtropicals, Orchard, Other Confined Animal Feeding Operations, Other row crops, Paved areas, Perennial forages, Perennial Forages Dairy Land Application, Rice, Sewage plant including ponds, Shrub/Scrub, Urban Commercial, Urban Industrial, Urban landscape, Urban residential, Vines, Warm season cereals/forages, Water, and Winter grains & safflower.

Meteorology Data

In WARMF, each land catchment was assigned the nearest available meteorology station with data of acceptable quality and quantity. Acceptable stations were identified through multiple steps of quality control and data processing.

All available data between 1921 and 2010 in the project region were collected from the California Irrigation Management Information System (CIMIS), the California Data Exchange Center (CDEC), the National Climatic Data Center (NCDC), the University of California Integrated Pest Management Touchstone Network, and the PestCast network. The majority of the stations reported only daily precipitation and temperature, though a few stations also reported cloud cover, dew point temperature, wind speed, and air pressure. If cloud cover (CC) was unavailable it was estimated from precipitation (P), average temperature (T_{ave}) and dewpoint temperature (T_{dew}) as follows:

When there is precipitation:

2 cm/day < P	CC = 1
1 cm/day < P ≤ 2 cm/day	CC = 0.9
0 cm.day < P ≤ 1 cm/day	CC = 0.8

When there is no precipitation:

$(T_{ave} - T_{dew}) < 4$ ˚C	CC = 0.6
4 ˚C ≤ $(T_{ave} - T_{dew}) < 6$ ˚C	CC = 0.3
6 ˚C ≤ $(T_{ave} - T_{dew})$	CC = 0

A thorough quality check was performed on the collected meteorological data to remove suspicious or infeasible values, such as outliers and repeated days/months/years of data. Missing data at each station were then filled using data at a nearby station(s) and an adjustment factor to account for climatic variations between stations. To verify the climatic consistency of the final, filled station data, each station's mean characteristics (e.g. mean annual precipitation and mean annual temperature) were calculated and compared to the same values and locations in PRISM datasets. PRISM datasets are high resolution spatial climate datasets produced at Oregon State University using sophisticated geospatial methodologies to account for climatic variations between meteorological station locations. If the characteristics of the filled station data were different from those found at the station's location within the PRISM data, an adjustment was applied to ensure that the filled data was consistent with long term climatic trends at the location. If differences were extremely large, the station was removed from further use as input to

WARMF. After this processing step, a total of 60 stations remained for use as input to WARMF. The stations and associated statistics are listed in Table 1.2 and their locations are shown in Figure 1-6.

Table 1.2 Meteorology Stations used for Input to WARMF

Station name	Mean Annual Precipitation, inches	Mean Annual Temperature, ^oF
Acampo	17.6	60.0
Auburn Municipal	34.0	61.4
Browns Valley	30.3	61.6
Bryte	16.8	62.5
Camp Pardee	21.4	61.5
Chico	25.7	62.3
Clearlake	26.7	56.9
Colgate	40.8	61.6
Colusa (CIMIS)	15.9	61.0
Colusa (NCDC)	15.7	61.4
Cottonwood Creek	35.8	55.5
Cow Creek	45.7	55.5
De Sabla	66.8	55.3
Durham	22.0	61.1
Fair Oaks	22.5	61.8
Fiddletown Dexter	36.4	55.8
Folsom	22.5	61.8
Gerber	23.0	61.7
Grass Valley	52.8	55.3
Indian Valley	22.9	56.4
Lodi	17.0	60.0
Lodi West	12.8	57.9
Manteca	11.4	58.8
Manzanita Lake	41.6	44.6
Marysville	22.6	63.1
Meridian	23.4	60.5
Mineral	54.6	44.8
Mineral II	54.6	44.8
Nicolaus	18.2	62.4
Nicolaus II	18.7	62.2
Oakdale	11.4	58.5
Orland	21.1	61.9
Oroville	26.7	62.1
Oroville Dam	35.1	62.0
Pacific House	50.5	59.7
Paradise	53.8	60.1
Paskenta	25.2	61.9
Placerville	38.4	57.4
Placerville II	47.0	59.6
Plymouth	31.9	55.8
Red Bluff	23.0	62.8
Redding	38.2	62.5
Redding Airport	30.8	63.6
Redding II	38.2	62.5

Station name	Mean Annual Precipitation, inches	Mean Annual Temperature, ^{o}F
Sacramento Exec Airport	19.2	61.9
Sacramento (NCDC)	18.1	62.3
Saddle Camp	29.6	54.4
Shingletown	49.2	52.0
Snow Mountain	66.1	45.5
Stockton	15.4	60.2
Stonyford	22.9	62.2
Stony Gorge	21.0	59.9
Sutter Hill	30.0	59.6
Tiger Creek	47.5	57.1
UCCE Sacramento	20.1	61.9
Upper Lake	45.6	56.6
Whiskeytown	62.2	60.6
Williams	15.8	61.8
Willows	18.8	61.4
Woodland	18.6	61.8

Each land catchment area in WARMF was assigned the nearest of the final 60 stations. However, in many cases the nearest station was located outside of the catchment area and/or large climatic variations occurred within a single catchment area (e.g. due to large elevation changes creating climatic variations not captured by the station network). Therefore precipitation weighting factors and temperature lapse rates were calculated to ensure that the spatial averages of precipitation and temperature across the catchment area were maintained. Similar to the station data adjustment procedure described above, the precipitation weighting factors and temperature lapse rates were calculated using PRISM datasets. First, the spatial average of annual precipitation and temperature were determined from the PRISM data for each catchment area. These values were then compared to the point mean annual precipitation and temperature of each catchment's assigned meteorological station. Precipitation weights were determined as the ratio of the PRISM spatial average annual precipitation to the station point average annual precipitation. Thus for example if the station data underestimated the catchment's spatial average precipitation (e.g. if the station is located at a point of low elevation as compared to the rest of the catchment area), the ratio was greater than 1 and thus the station data was scaled up for that catchment to account for the difference. Temperature lapse rates were determined similarly, though as the difference (rather than ratio) between the PRISM spatial average temperature and the station point average temperature. Catchment temperature values were determined by subtracting the lapse rate from the station temperature data. Thus a negative lapse rate indicates that the overall catchment area is warmer than the assigned station's temperature values.

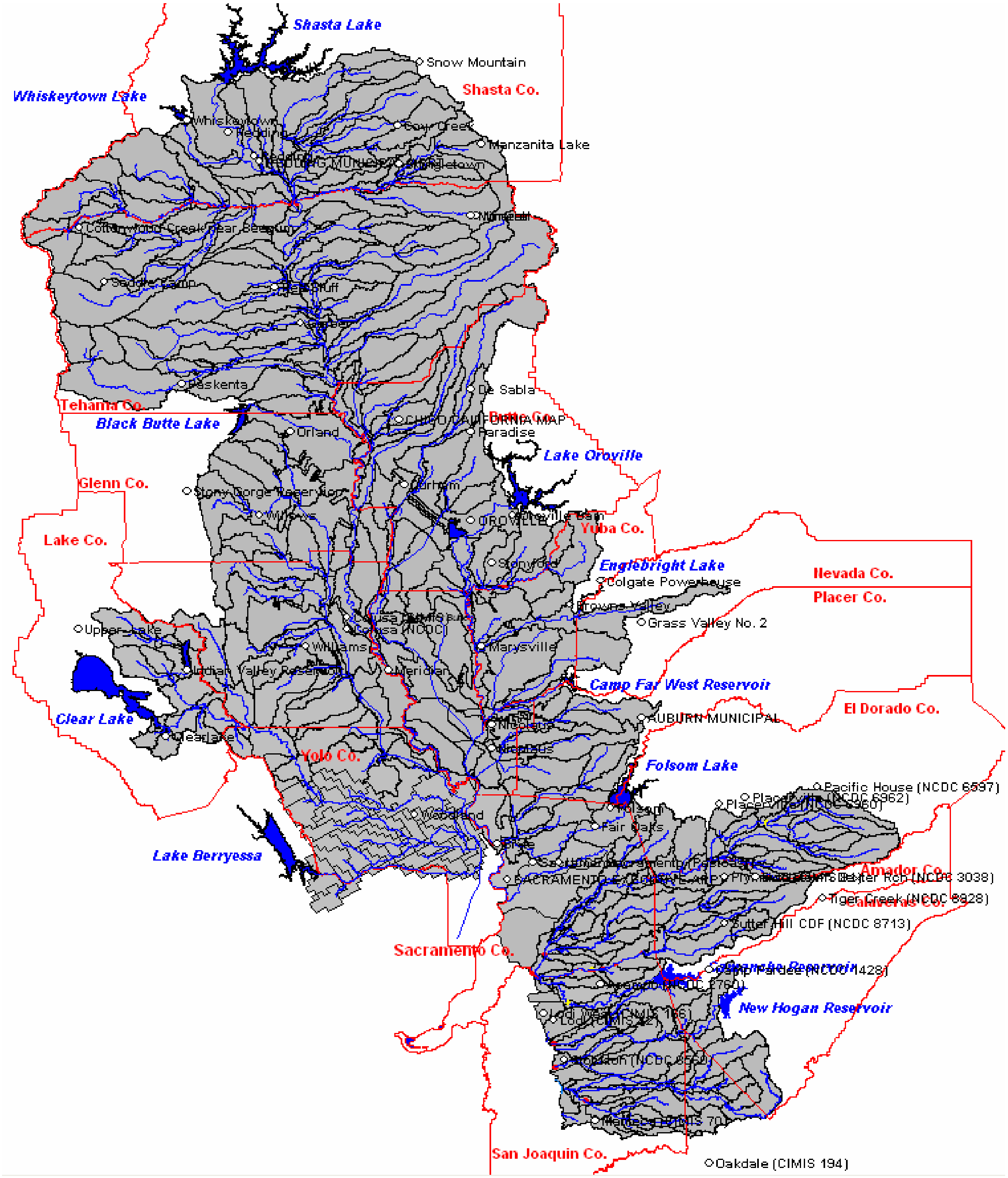

Figure 1-6 Locations of Meteorology Stations in the Sacramento River Watershed

Air Quality and Rain Chemistry Data

Air quality data were used to calculate the dry deposition of atmospheric ammonia, nitrate, and other constituents to the land and canopy surfaces. Weekly air quality data were obtained from the US EPA's Clean Air Status and Trends Network (CASTNET) sites at Lassen Volcanic National Park and Yosemite National Park.

Rain chemistry data was used to calculate wet deposition falling onto each of the land catchments. Data for rain chemistry were compiled from five National Atmospheric Deposition Program (NADP) sites in the vicinity of the Sacramento River drainage basin: Hopland, Sagehen Creek, Davis, Lassen Volcanic National Park and Yosemite National Park. Data from these stations were entered on a weekly basis for input to the WARMF model. The locations of the five sites in relation to the WARMF model domain are depicted in Figure 1-7.

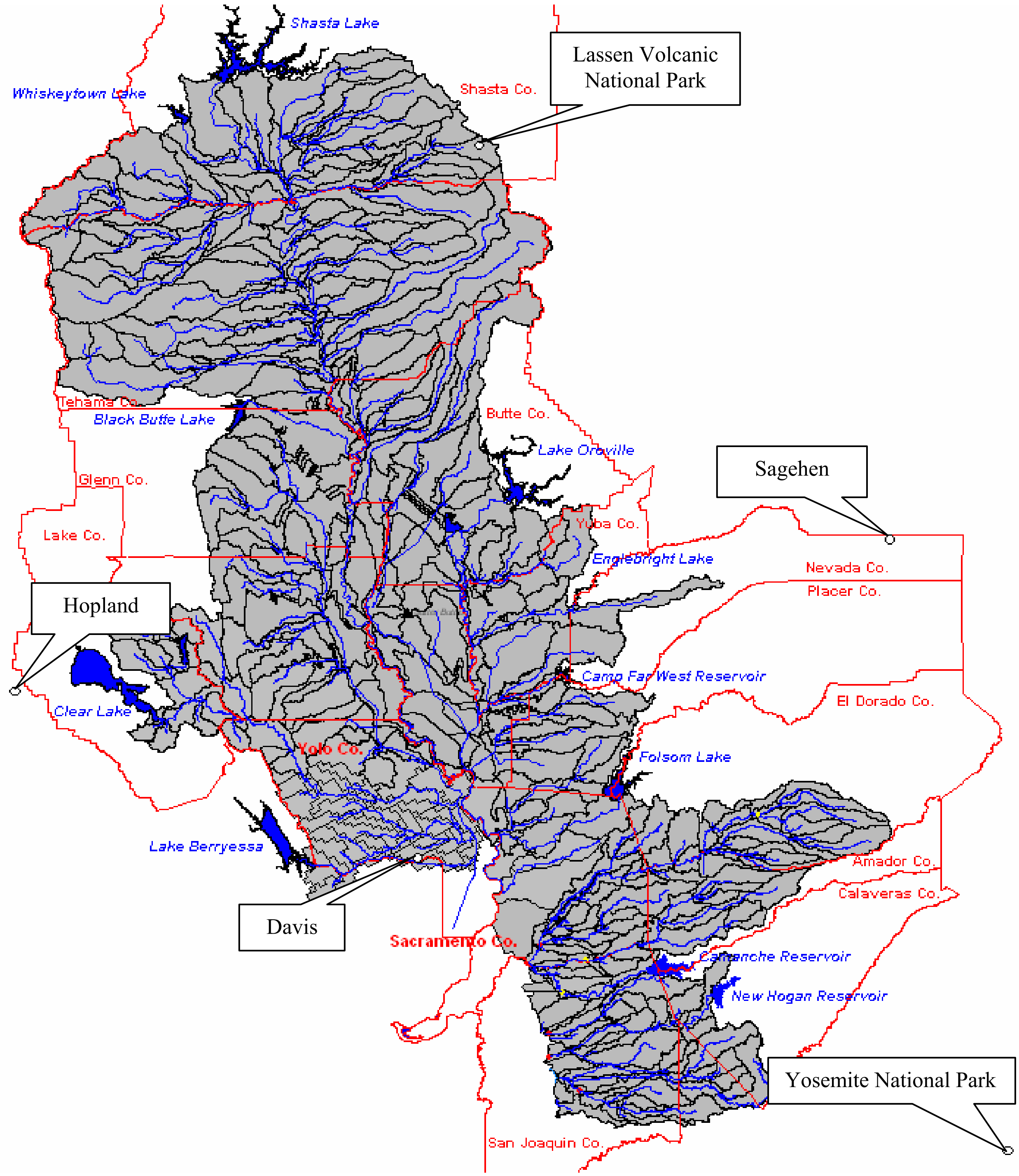

Figure 1-7 Air quality and precipitation chemistry data collection locations in the vicinity of the Sacramento River WARMF model domain.

Boundary River Inflows

Boundary river inflows were external inputs to the WARMF model. These inputs were treated like "point sources", with time series data defining the quantity and quality of water flowing across (from outside to inside) the modeled watershed boundary. Table 1.3 lists the boundary river inflows and their associated data sources. All twelve inflows are located just below major reservoirs, including the Sacramento River below Shasta Lake in the north, four west side tributaries (Clear Creek below Whiskeytown Lake, Stony Creek below Black Butte Lake, Cache Creek below Clear Lake, and Putah Creek below Lake Berryessa) and seven east side tributaries (Feather River below Lake Oroville, Feather River below Thermalito Afterbay, Yuba River below Englebright Lake, Bear River below Camp Far West Reservoir, American River below Folsom Lake, Mokelumne River Below Camanche Reservoir, and the Calaveras River below New Hogan Reservoir).

All available data for daily flow, temperature, and water quality constituent concentrations at the boundary river inflows were collected for the modeling period (1921-2010). Data availability varied greatly between the twelve inflows and also between the various constituents at each station. In all cases, daily flow data were available to create continuous time series for the latter half (1970-2010) of the modeling period. However, in many cases flow data were unavailable for some portion of the early part of the modeling period (before 1970). In those cases, flow was either taken from a nearby downstream station or was assumed to be zero.

Temperature and water quality data were much sparser than flow data and rarely available on a daily basis. Two steps were carried out to fill the data in order to generate a complete daily time series. First, nearby downstream stations were used to fill as much missing data as possible at the primary water quality station(s) near the inflow location. Second, default daily values were determined for an average year based on all of the available observations for each constituent. To do so, monthly average concentrations were first calculated using all of the observations that existed for each month. If no observations were ever collected in a particular month, that month's value was interpolated from the surrounding months. If no data were available for any months for a particular constituent, the monthly averages were estimated from another boundary river inflow of likely similar water quality characteristics (as noted below Table 1.3). The resulting monthly average concentrations were assigned to the 15th of each month and values in between were interpolated (i.e. between the 15^{th} of a given month and the 15^{th} of the prior or following month) to determine the default concentration for each day of the year. If observations were missing for a period of 90 days or longer, the default values were used to fill that portion of the time series. To prevent sharp changes in the resulting time series, a blending algorithm was used to gradually shift chemical concentrations from the last observed value to the default values. For missing periods shorter than 90 days, time series values were interpolated between observations.

For periods of the time series when the daily default values were used (i.e. missing periods greater than 90-days), additional adjustments were applied when possible to further improve the estimates. Specifically, if electrical conductivity (EC) measurements were available, the default ion concentrations were scaled up or down in equal proportions so that their sum multiplied by 1.5 was equal to the EC observations (since the sum of ions is the total dissolved solids (TDS), which multiplied by 1.5 is roughly equal to EC in μs/cm). If measurements of alkalinity were also available, additional adjustment factors for cations and anions were calculated in order to simultaneously match the measured values of EC and alkalinity.

Table 1.3 Data Sources for Boundary River Inflows

Upstream Boundary	Source(s) of Flow Data	Sources of Water Quality Data
Sacramento River at Shasta Dam	Sacramento River at Keswick (USGS 11370500)	Sacramento River at Keswick (USGS 11370500, Bur. Rec. RSA568, CDEC KWK, DWR A2101000)
Clear Creek at Whiskeytown Dam	Clear Creek near Igo (USGS 11372000)	Clear Creek above Paige Bar (DWR) Clear Creek near Igo (USGS 11372000, CDEC IGO) Clear Creek near Mouth [1] (DWR) Sacramento River at Keswick [2] (same stations as listed above)
Stony Creek at Black Butte Dam	Stony Creek below Black Butte Dam (USGS 11388000, CDEC BLB)	Stony Creek below Black Butte Dam (DWR, USACE, BDAT, USGS 11388000) Sacramento River at Keswick [3] (same stations as listed above)
Cache Creek below Clear Lake	Cache Creek below Lower Lake (USGS 11451000)	Cache Creek near Lower Lake (CAWRCB A8135000) Cache Creek NF nr Lower Lake [4] (USGS 11451500, CAWRCB A8205000) Cache Creek nr Rumsey [4] (USGS 11451760)
Putah Creek below Lake Berryessa	Putah Creek near Winters, CA (USGS 11454000)	Putah Creek near Winters, CA (USGS 11454000)
Feather River at Oroville Dam	Feather at Oroville (USGS 11407000)	Feather at Oroville (USGS 11407000, CAWRCB A0519100) Feather nr Gridley [5] (DWR, CDEC GRL, CAWRCB A0516500, USGS 11407150) Bear River near Wheatland [6] (USGS 11424000)
Feather River below Thermalito Afterbay	Thermalito Afterbay release to Feather R (USGS 11406920)	Thermalito Afterbay at Feather R (CAWRCB TA001000) Feather at Oroville [7] (USGS 11407000, CAWRCB A0519100)
Yuba River at Englebright Dam	Yuba R below Englebright Dam nr Smartville (USGS 11418000)	Yuba R Below Englebright Dam nr Smartville (USGS 11418000, CDEC YRS) Yuba R below Dry Creek [8] (USGS 11421500, CAWRCB A0615000)
Bear River at Camp Far West Dam	Bear River near Wheatland (USGS 11424000)	Bear River near Wheatland (USGS 11424000) Bear River at Mouth [9] (DWR, CAWRCB A0651201) Feather at Oroville [10] (USGS 11407000, CAWRCB A0519100)
American River at Folsom Dam	American R at Fair Oaks (USGS 11446500)	American R at Folsom (EPA STORET A7111601 & A7R84271087, USGS 11446200) American R near Fair Oaks [11] (CAWRCB A0718000 & WB00SCRM198, USGS 11446400 & 11446500)

Upstream Boundary	Source(s) of Flow Data	Sources of Water Quality Data
Mokelumne River at Camanche Dam	Mokelumne R below Camanche Dam (USGS 11323500)	Mokelumne R below Camanche Dam (USGS 11323500, CADWR - SWAMP Site 531SJC512, East Bay Municipal Utilities District - MSElliott) Camanche Reservoir (East Bay Municipal Utilities District - CAMD)
Calaveras River at New Hogan Dam	Calaveras River below New Hogan Dam (CDEC NHG, USGS 11308900, USGS 11309500)	Calaveras R below New Hogan Dam (EPA STORET B2530000 & 405) New Hogan Reservoir (EPA STORET B2R80910485, B2R80920481 & 403)

[1] Downstream station used to fill water quality data where primary stations were missing.
[2] No data was available on Clear Creek for organic carbon, dissolved oxygen, suspended sediment or BOD. Default daily values for these constituents were derived from average concentrations at Sacramento at Keswick.
[3] No data was available on Stony Creek for BOD. Default daily values for this constituent were derived from average concentrations at Sacramento at Keswick.
[4] Downstream stations used to fill water quality data if data at primary station(s) were missing.
[5] Downstream stations used to fill water quality data if data at primary station(s) were missing.
[6] No data was available on Feather River for organic carbon. Default daily values for this constituent were derived from average concentrations in the Bear River near Wheatland.
[7] Only temperature data was available for Thermalito Afterbay. All other water quality constituent data were taken from the upstream station, Feather River at Oroville.
[8] Downstream stations used to fill water quality data if data at primary station(s) were missing.
[9] Downstream stations used to fill water quality data if data at primary station(s) were missing.
[10] No data was available on Bear River for inorganic carbon. Default daily values for this constituent were derived from average concentrations in the Feather River at Oroville.
[11] Downstream stations used to fill water quality data if data at primary station(s) were missing.

Point Source Discharge Data

A large number of point source discharges exist in the Sacramento Watershed. The locations for 107 point source discharges to rivers and tributaries inside the model domain were identified and defined in the WARMF model. However, flow and/or water quality data were available for only 33 of the 107 locations. The remaining 74 point source discharges were defined in the model with flow and concentrations of zero in case data becomes available at a later date. The station names, locations and mean annual flows of the 33 point source discharges with data are listed in Table 1.4. Data from the most significant of the point source discharges (The Sacramento Regional Wastewater Treatment Plant) was extrapolated with estimates to obtain a complete record for the modeling period of 1921-2010. Information about current population and population growth since 1921 were used to scale values of typical wastewater treatment plant effluent to get appropriate estimates for the Sacramento wastewater treatment plant. The 86 stations with no data are listed in Table 1.5.

Table 1.4 Point Source Discharges with Data

Name	NPDES	County	Lat	Long	Mean Annual Flow (cfs)
ANDERSON WPCP	CA0077704	Shasta	40.47	-122.28	1.5
CLEAR CREEK WWTP	CA0079731	Shasta	40.50	-122.37	12.6
COTTONWOOD WWTP	CA0081507	Shasta	40.40	-122.25	0.2
REDDING, CITY OF	CA0082589	Shasta	40.47	-122.29	4.3
SHASTA LAKE WWTP WQC	CA0079511	Shasta	40.66	-122.39	1.98
CORNING WWTP	CA0004995	Tehama	39.91	-122.12	1.26
MOLDED PULP MILL ISW	CA0004821	Tehama	40.17	-122.23	2.4
RED BLUFF CITY	CA0078891	Tehama	40.16	-122.22	1.8
WILLOWS WWTP	CA0078034	Glenn	39.50	-122.19	1.35
SC-Oroville WWTP	CA0079235	Butte	39.49	-121.56	4.8
CHICO WWTP	CA0079081	Butte	39.68	-121.93	11.7
COLUSA WWTP	CA0078999	Colusa	39.25	-122.06	0.8
CITY OF LIVE OAK WWTP	CA0079022	Sutter	39.26	-121.68	0.85
YUBA CITY WWTP	CA0079260	Sutter	39.11	-121.61	8.0
BEALE AIR FORCE BASE	CA0110299	Yuba	39.13	-121.39	0
LINDA CO. WATER DISRICT WATER POLLUTION CONTROL PLANT	CA0079651	Yuba	39.10	-121.58	1.86
OLIVEHURST PUD WWTP	CA0077836	Yuba	38.89	-121.11	3.5
NEVADA CITY WWTP	CA0079901	Nevada	39.26	-121.03	0.6
AUBURN WWTP	CA0077712	Placer	38.89	-121.10	2.2
LINCOLN	CA0084476	Placer	38.90	-121.34	5.4
PLACER CO DFS	CA0079367	Placer	38.80	-121.13	2.6
PLACER COUNTY SMD 1 WWTP	CA0079316	Placer	38.96	-121.11	2.9
PLEASANT GROVE WWTP	CA0084573	Placer	38.79	-121.38	10.8
ROSEVILLE WWTP CITY OF (Dry Ck)	CA0079502	Placer	38.74	-121.29	16.6
CITY OF SACRAMENTO COMBINED WWTP	CA0079111	Sacramento	38.52	-121.50	612
SACRAMENTO REGIONAL SANITATION DIST.	CA0077682	Sacramento	38.45	-121.46	243
CACHE CREEK INDIAN BINGO	CAU000541	Yolo	38.73	-122.14	0.3
CITY OF DAVIS STP	CA0079049	Yolo	38.59	-121.67	9.1
CITY OF WOODLAND WWCF	CA0077950	Yolo	38.66	-121.87	8.8
UNIVERSITY OF CALIFORNIA DAVIS	CA0077895	Yolo	38.54	-121.75	2.9
WEST SACRAMENTO WWTP	CA0079171	Yolo	38.56	-121.52	8.7
GALT WWTP	CA0081434	Sacramento	38.27	-121.31	3.3
SACRAMENTO MUD – RANCHO SECO	CA0004758	Sacramento	38.36	-121.09	16.0

Table 1.5 Point Source Discharges with No Data

Name	NPDES	County	Lat	Long
AC POWDER COATING	CAP000111	Shasta	40.44	-122.29
ANDERSON WPCP	CA0077704	Shasta	40.47	-122.28
BELLA VISTA WTP	CA0080799	Shasta	40.60	-122.35
CALARAN SAWMILL	CAU000089	Shasta	40.57	-122.37
CALAVERAS CEMENT COMPANY	CA0081191	Shasta	40.73	-122.32
CALIFORNIA OIL RECYCLERS INC	CAU000084	Shasta	40.52	-122.38
CLEAR CREEK WTP	CA0083828	Shasta	40.60	-122.54
COLEMAN FISH HATCHERY	CA0004201	Shasta	40.40	-122.18
FOOTHILL HIGH SCHOOL CSW WQC	CAU000394	Shasta	40.59	-122.40
INDUSTRIAL OPTICS	CAP000113	Shasta	40.45	-122.30
MILLSEAT FACILITY	CA0082279	Shasta	40.48	-121.86
MOUNTAIN GATE QUARRY	CA0084140	Shasta	40.73	-122.31
SEWAGE DISPOSAL PONDS	CAU000193	Shasta	40.71	-122.34
SHASTA LAKE WTF	CA0004693	Shasta	40.71	-122.41
SHEA CONSTRUCTION	CA0083097	Shasta	40.73	-122.32
SIERRA PACIFIC-ANDERSON	CA0082066	Shasta	40.47	-122.32
SIERRA PACIFIC-SHASTA LAKE	CA0081400	Shasta	40.68	-122.38
TARGET T615	CAU000083	Shasta	40.59	-122.35
US BUREAU OF REC	CA0084298	Shasta	40.69	-122.39
VOORWOOD CO	CAP000112	Shasta	40.45	-122.29
WHEELABRATOR SHASTA	CA0081957	Shasta	40.43	-122.28
WILLIAM HOBLIN	CAU000220	Shasta	40.61	-122.28
BELL-CARTER FOODS INC	CA0081639	Tehama	39.93	-122.18
DALES FACILITY	CA0080381	Tehama	40.37	-122.02
DARRAH SPRINGS HATCHERY	CA0004561	Tehama	40.41	-121.98
MEADOWBROOK FACILITY	CA0080373	Tehama	40.18	-122.24
MT LASSEN TROUT FARMS	CA0082104	Tehama	40.32	-121.97
TEHAMA COUNTY OF	CAU000168	Tehama	40.18	-122.24
WOODSON BRIDGE ESTATES	CAU000201	Tehama	39.91	-122.11
BALDWIN CONTRACTING	CAU001022	Glenn	39.78	-122.20
CITY OF ORLAND WTP	CAU000444	Glenn	39.75	-122.19
BIGGS, CITY OF	CA0078930	Butte	39.41	-121.72
FEATHER RIVER HATCHERY	CA0004570	Butte	39.52	-121.55
GRIDLEY PIT STOP	CAU000223	Butte	39.35	-121.69
NORTH STATE RENDERING	CAU000192	Butte	39.59	-121.69
NORTH YUBA WD	CA0084824	Butte	39.51	-121.27
OROVILLE WYANDOTTE ID	CA0083143	Butte	39.51	-121.46
PID WTP	CA0083488	Butte	39.81	-121.58
THERMALITO ANNEX HATCHERY	CA0082350	Butte	39.49	-121.69
MAXWELL PUD	CA0079987	Colusa	39.28	-122.19
CALPINE SUTTER ENERGY CENTER	CA0081566	Sutter	39.11	-121.69
LAKE WILDWOOD WWTP	CA0077828	Nevada	39.23	-121.22
ADVANCED METAL FINISHING LLC	CAP000103	Placer	38.95	-121.08
CARPENTER ADVANCED CERAMICS	CAP000108	Placer	38.95	-121.08
CERONIX	CAP000107	Placer	38.95	-121.08
COHERENT INC AUBURN GROUP	CAP000104	Placer	38.95	-121.08
CUSTOM POWDER COATING	CAP000102	Placer	38.95	-121.09
FORMICA CORPORATION	CA0004057	Placer	38.82	-121.31
SA NO28, ZONE NO6	CA0079341	Placer	38.98	-121.37

Name	NPDES	County	Lat	Long
SIERRA PLATING	CAP000105	Placer	38.95	-121.10
UNION PACIFIC ROSEVILLE	CAU000049	Placer	38.73	-121.31
UNITED AUBURN INDIAN COMMUNITY	CA0084697	Placer	38.84	-121.31
VIAN ENTERPRISES	CAP000106	Placer	38.93	-121.09
A C & W - GW TREATMENT	CA0083992	Sacramento	38.57	-121.30
AEROJET GENERAL CORPORATION	CA0004111	Sacramento	38.61	-121.20
ALTA PLATING INCORPORATED	CAP000027	Sacramento	38.57	-121.49
ASIAN AUTO RECYCLING	CAU000678	Sacramento	38.57	-121.26
BLOMBERG WINDOW SYSTEMS	CAP000026	Sacramento	38.51	-121.50
CAPITAL AUTO PARTS/TOWING	CAU000663	Sacramento	38.69	-121.41
EURO STARS DISMANTLING INC.	CAU000689	Sacramento	38.58	-121.26
EXTREME AUTO DISMANTLING	CAU000680	Sacramento	38.58	-121.26
GSV AUTO DISMANTLERS	CAU000682	Sacramento	38.58	-121.26
K & G AUTO DISMANTLER	CAU000683	Sacramento	38.57	-121.26
NIMBUS HATCHERY	CA0004774	Sacramento	38.63	-121.22
OFFICE OF STATE PUBLISHING	CA0078875	Sacramento	38.59	-121.49
RANCHO AUTO AUCTION	CAU000685	Sacramento	38.56	-121.25
RUEBEN E LEE RESTAURANT	CAU000042	Sacramento	38.60	-121.42
SACRAMENTO FACILITY	CA0082961	Sacramento	38.53	-121.39
SACRAMENTO IU	CAP000094	Sacramento	38.58	-121.49
SEVEN UP BOTTLING CO OF SAN FRANCISCO	CAU000584	Sacramento	38.62	-121.43
SILGAN CAN COMPANY	CAP000093	Sacramento	38.51	-121.47
STATE OF CALIFORNIA GENERAL SERVICES	CA0078581	Sacramento	38.57	-121.50
MCCLELLAN AIR FORCE BASE CA	CA0081850	Sacramento	38.66	-121.40
ZAPAD	CAU000672	Sacramento	38.58	-121.49
CHOPAN AUTO DISMANTLING	CAU000665	Yolo	38.58	-121.55
DAN'S MISSION TOWING	CAU000666	Yolo	38.58	-121.55
GENESIS AUTO DISMANTLER	CAU000667	Yolo	38.58	-121.55

Fertilizer Application Data

WARMF allows for monthly land application loading inputs for each land use. Land application represents any loading to the land surface which does not come from the atmosphere. It includes fertilizer in agricultural and urban land uses and disposal of animal waste from dairies and other confined feeding operations. The application rates used were estimated by NewFields Agriculture and Environmental Resources based on agricultural practices in the Sacramento River watershed. The nitrogen and phosphorus application rates used in WARMF are shown in Table 1.6.

Table 1.6 Land Application Rates

Land Use	Ammonia Application Rate, lbs N/acre/yr	Sulfate Application Rate, lbs/acre/yr	Nitrate Application Rate, lbs N/acre/yr	Phosphate Application Rate, lbs P/acre/yr	Application Months
Barren land					
Cotton	215	727		7	4-10
DairyPA		5	120	6	5-9
Deciduous Forest					
Double Crop DLA	474	1462	25	50	3-9
Evergreen Forest					
Fallow					
Farmsteads	27	69	7		5-9
Flowers and nursery	119		119	7	2-9
Grassland / Herbaceous					
Lagoon	684	745		186	1-12
Marsh					
Mixed Forest					
Native Classes, Unsegregated					
Olives, citrus & subtropicals	317	1076		7	3-10
Orchard	239	809		7	4-10
Other CAFOs	245	95	236	22	1-12
Other row crops	194	580	21	7	5-9
Paved areas					
Perennial forages	119	399		7	3-11
Perennial Forages DLA	580	1787	30	61	3-11
Rice	110	378		23	4-6
Sewage plant incl. ponds					
Shrub/Scrub					
Urban Commercial	12	21	3	6	4-10
Urban Industrial	6	5	2	6	4-10
Urban landscape	157	393	39	6	3-11
Urban residential	56	134	14	6	3-11
Vines	105	259	27	7	4-9
Warm season cereals/forages	30	101		7	4-8
Water					
Winter grains & safflower	20	67		7	3-5

Irrigation Water Distribution

Irrigation from 56 federal, state and private water districts was simulated in the WARMF Sacramento River model. Where the district boundaries overlapped the land catchment boundaries, irrigation water was applied to the land in the model. The irrigation waters were diverted from various sources shown in Table 1.7. Many additional smaller diversions, often for individual farms, were also included in the model.

Table 1.7 Sources of Irrigation Water

Irrigation District Name	Water Source
4-M W.D.	Sacramento River upstream of Hamilton City
Anderson-Cottonwood I.D.	Sacramento River upstream of Bend Bridge
Arbuckle P.U.D.	Cottonwood Creek, Middle Fork
Biggs-West Gridley W.D.	Sutter-Butte Main Canal
Browns Valley I.D.	Yuba river
Camp Far West I.D.	Bear River
Capay Rancho W.D.	Pine Creek
Colusa County W.D.	Sacramento River upstream of Hamilton City
Colusa Properties	Sacramento River upstream of Verona
Cordua Irrigation District	Yuba River
Cortina W.D.	Sacramento River upstream of Hamilton City
Davis W.D. (Tc)	Sacramento River upstream of Hamilton City
Deseret Farms Of California	Sacramento River upstream of Hamilton City
Dunnigan W.D.	Sacramento River upstream of Hamilton City
El Dorado I.D.	Carson Creek, Sly Park Creek
Galt I.D.	Laguna Creek
Glenn Colusa I.D.	Sacramento River upstream of Hamilton City
Glenn Valley W.D.	Sacramento River upstream of Hamilton City
Glide W.D.	Sacramento River upstream of Hamilton City
Holthouse W.D.	Sacramento River upstream of Hamilton City
Jackson Valley I.D.	Jackson Creek
Kanawha W.D.	Sacramento River upstream of Hamilton City
Kirkwood W.D.	Sacramento River upstream of Hamilton City
Knights Landing Service Dist.	Sacramento River upstream of Verona
La Grande W.D.	Sacramento River upstream of Hamilton City
M And T Chico Ranch Inc.	Sacramento River upstream of Hamilton City
Maxwell I.D.	Sacramento River upstream of Hamilton City, Sacramento River upstream of Verona, Colusa Basin Drainage Canal
Meridian Farms Water Co.	Sacramento River upstream of Verona
Myers-Marsh M.W.C.	Sacramento River upstream of Hamilton City
Natomas Central M.W.D.	Sacramento River upstream of Verona
Nevada I.D.	Yuba River, Bear River
Newhall Land & Farming Co.	Sacramento River upstream of Verona
North Delta Water Agency	Putah Creek
North San Joaquin W.C.D.	Mokelumne River
Oji Brothers Farm, Inc.	Sacramento River upstream of Verona
Olive Percy Davis (Davis Ranches)	Colusa Basin Drainage Canal, Sacramento River upstream of Verona
Omochumne-Hartnell W.D.	Cosumnes River, Deer Creek
Orland-Artois W.D.	Sacramento River upstream of Hamilton City
Paradise Irrigation District	Little Butte Creek
Pelger M.W.C.	Sacramento River upstream of Verona
Pleasant Grove-Verona M.W.C.	Sacramento River upstream of Verona
Princeton-Codora-Glenn I.D.	Sacramento River upstream of Verona, Willow Creek

Irrigation District Name	Water Source
Provident I.D.	Sacramento River upstream of Hamilton City, Sacramento River upstream of Verona, Willow Creek
Putah South Canal	Putah Creek
Reclamation District 1004	Sacramento River upstream of Verona
Reclamation District 108	Sacramento River upstream of Verona
River Garden Farms Co.	Sacramento River upstream of Verona
Roberts Ditch Co.	Sacramento River upstream of Verona
Sutter Mutual Water Company	Sacramento River upstream of Verona
The Oji's	Sacramento River upstream of Verona
Thermalito Irrigation District	Feather River
Tisdale I. & D.C.	Sacramento River upstream of Verona
Tisdale I. & D.C. Service Area	Sacramento River upstream of Verona
Westside W.D.	Sacramento River upstream of Hamilton City
Woodbridge I.D.	Mokelumne River
Yolo County FC & WCD	Cache Creek

The locations of all water diversions from the Sacramento River and its tributaries are shown with white dots in Figure 1-8. The timing of irrigation withdrawals was determined based on the best available data for each of the diversions included in the WARMF Sacramento River simulation. During time periods when measured diversion data exist (see Table 1.8), water withdrawals were simulated using these data. During other periods, irrigation withdrawals were estimated by calculating monthly averages from the existing data then populating the diversion file with this information. Diversion water withdrawal data were unavailable for many of the diversions simulated. These diversions were simulated using the permitted withdrawal quantities, distributed throughout the year according to a distribution of monthly water withdrawals synthesized from timing information from other diversion locations with available data.

Each of the irrigation diversions included in the model were simulated dynamically by WARMF. For each diversion, WARMF diverts the quantity of irrigation water from their respective diversion point(s), and applies the water to specified land use types contained within each of the land catchments intersecting the irrigation district boundary. The chemical composition of the diverted water is defined by the WARMF simulation of the river segment from which each is taken.

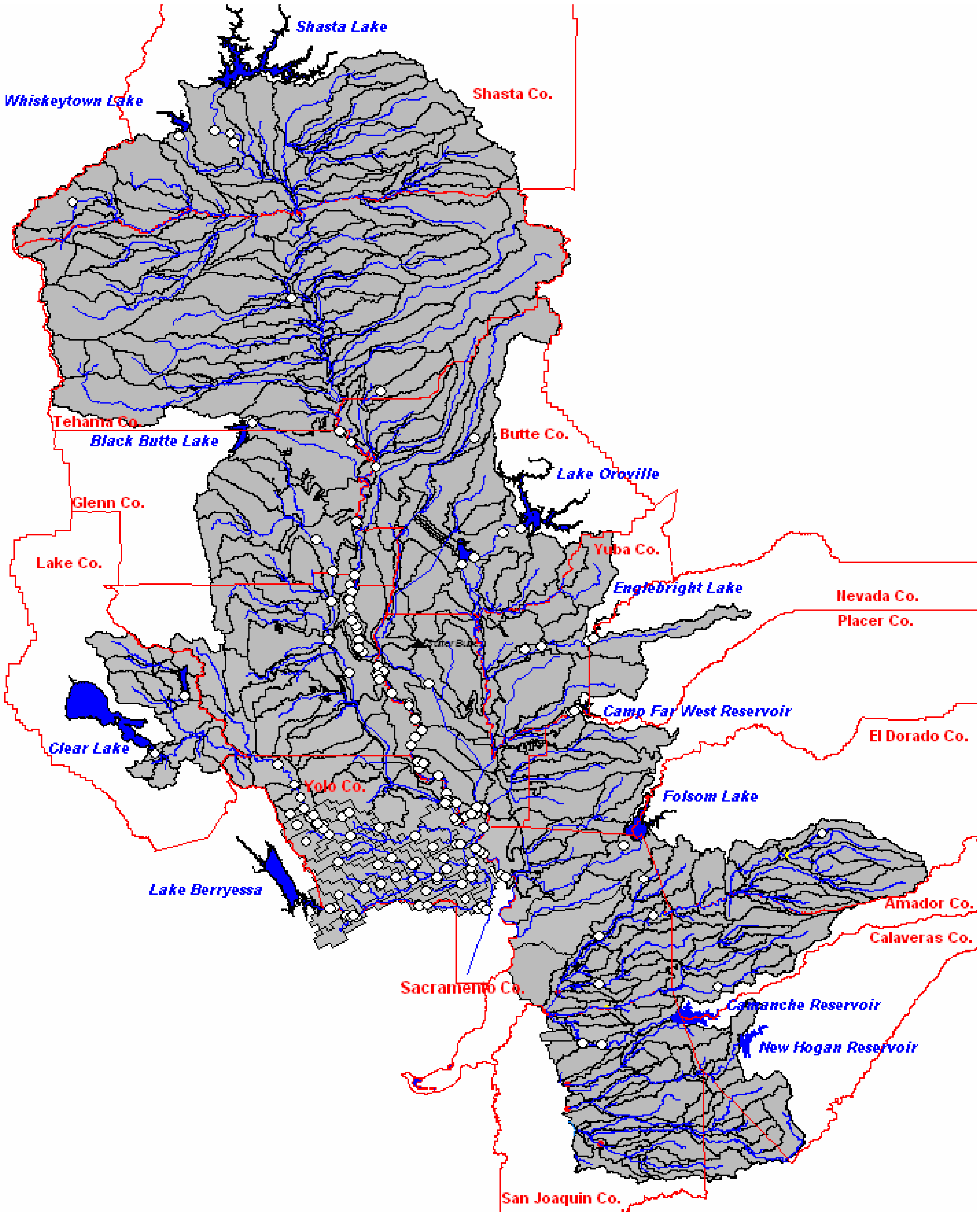

Figure 1-8 Locations (as indicated by the white dots) of water diversions from the Sacramento River and its tributaries.

Table 1.8 Diversions of Irrigation Water in the WARMF Sacramento River model domain.

Diversion	Data Available	Average Diversion Flow (ft^3/sec)
4-M W.D.	Calculated from Demand	2.9
Anderson-Cottonwood I.D.	Jan 1991 - Sept 2008	134.1
Arbuckle P.U.D.	Nov 1997 - Apr 2007	23.3
Biggs-West Gridley W.D.	Calculated from Annual Permit	222.5
Browns Valley I.D.	Calculated from Demand	17.8
Camp Far West I.D.	Calculated from Annual Permit	25.5
Capay Rancho W.D.	Calculated from Demand	0.8
Colusa County W.D.	Calculated from Demand	76.2
Colusa Properties	Calculated from Annual Permit	2.8
Cordua Irrigation District	Oct 1987 - Oct 1991	135.2
Cortina W.D.	Calculated from Demand	1.4
Davis W.D. (Tc)	Calculated from Annual Permit	2.8
Deseret Farms Of California	Calculated from Demand	1.7
Dunnigan W.D.	Calculated from Demand	18.1
El Dorado I.D.	Calculated from Demand	40
Galt I.D.	Calculated from Demand	14.6
Glenn Colusa I.D.	Jan 1993 - Dec 2007	870.3
Glenn Valley W.D.	Calculated from Demand	1.1
Glide W.D.	Calculated from Demand	18.8
Holthouse W.D.	Calculated from Demand	2.1
Jackson Valley I.D.	Calculated from Demand	14.6
Kanawha W.D.	Jan 1993 - Dec 2007	40.1
Kirkwood W.D.	Calculated from Demand	1.0
Knights Landing Service Dist.	Jan 2007 - Dec 2007	1.2
La Grande W.D.	Calculated from Demand	6.9
M And T Chico Ranch Inc.	Calculated from Demand	12.4
Maxwell I.D.	Jan 1993 - Dec 2007	70.6
Meridian Farms Water Co.	Calculated from Demand	32.8
Myers-Marsh M.W.C.	Jan 1993 - Dec 2007	0.4
Natomas Central M.W.D.	Calculated from Demand	110.5
Nevada I.D.	Calculated from permitted withdrawal	102.2
Newhall Land & Farming Co.	Jan 1993 - Dec 1993	50.2
North Delta Water Agency	Calculated from Demand	2.8
North San Joaquin W.C.D.	Calculated from Demand	27.6
Oji Brothers Farm, Inc.	Jan 1993 - Dec 2007	10.0
Olive Percy Davis	Jan 1993 - Dec 2004	66.4
Omochumne-Hartnell W.D.	Calculated from Demand	72.9
Orland-Artois W.D.	Calculated from Demand	71.4
Paradise Irrigation District	Calculated from permitted withdrawal	25.3
Pelger M.W.C.	Calculated from Demand	7.0
Pleasant Grove-Verona M.W.C.	Calculated from Demand	21.8
Princeton-Codora-Glenn I.D.	Jan 1993 - Dec 2007	96.7
Provident I.D.	Jan 1993 - Dec 2007	189.9
Putah South Canal	Oct 1994 – Sep 2008	252.3

Diversion	Data Available	Average Diversion Flow (ft^3/sec)
Reclamation District 1004	Calculated from Demand	80.1
Reclamation District 108	Calculated from Demand	192.0
River Garden Farms Co.	Jan 1993 - Dec 2007	31.0
Roberts Ditch Co.	Calculated from Demand	4.3
Sutter Mutual Water Company	Jan 1993 - Dec 2007	266.7
The Oji`S	Calculated from Demand	3.0
Thermalito Irrigation District	Calculated from permitted withdrawal	22.7
Tisdale I. & D.C.	Calculated from Demand	9.3
Westside W.D.	Calculated from Demand	44.7
Woodbridge I.D.	Apr 1926 – Sep 2009	116.4
Yolo County FC & WCD	Jan 1975 - Sep 2008	215.3

The quantity of irrigation water applied within each land catchment was calculated using a geographic information system (GIS). In the GIS, an intersection between layers representing the WARMF catchments and the irrigation district boundaries was created. The resulting layer was then employed to query a land use dataset to determine the land use distribution within each irrigation district present within each of the WARMF catchments. The calculated areas of each irrigated land use were used to estimate the demand for irrigation water within each of the WARMF catchments. Irrigation requirements for various land uses are shown in Table 1.9.

Table 1.9 Applied Water Rates (feet/year)

Land Use Class	CIMIS Evapotranspiration Zone[1]						
	8	10	11	12	13	14	15
Cotton	3.4	3.2	N/A	4.2	N/A	4.3	4.6
Double Crop DLA	N/A	N/A	N/A	4.6	N/A	4.2	4.5
Farmsteads	4.0	3.4	4.4	5.3	4.1	5.4	6.0
Flowers and nursery	1.9	N/A	N/A	2.6	2.0	2.7	3.0
Olives, citrus, and subtropicals	1.9	N/A	2.2	2.6	2.0	2.7	3.0
Orchard	2.8	2.5	3.2	3.7	3.1	3.8	4.0
Other row crops	3.2	3.0	N/A	3.7	3.6	3.9	4.0
Perennial forages	3.7	3.1	4.1	4.9	3.8	5.0	5.6
Perennial forages DLA	N/A	N/A	N/A	4.9	N/A	5.0	5.6
Rice	3.4	N/A	N/A	3.9	3.8	4.1	4.2
Urban commercial	2.2	1.8	2.4	2.9	2.3	2.9	3.2
Urban industrial	2.2	1.8	2.4	2.9	2.3	2.9	3.2
Urban landscape and open space	3.5	2.9	3.8	4.6	3.6	4.7	5.2
Urban residential	4.0	3.4	4.4	5.3	4.1	5.4	6.0
Vines	1.7	1.5	1.9	2.2	1.8	2.3	2.5
Warm season cereals and forages	3.1	2.9	3.3	3.6	3.4	3.7	3.9
Winter grains and safflower	0.6	0.2	0.6	1.2	0.3	1.2	1.6

[1]Values of N/A represent combinations of land use class and evapotranspiration zone that do not exist within the WARMF model domain

In the Cache and Putah Creek watersheds in Yolo County, a detailed linkage between WARMF and the CVHM groundwater model (Faunt 2009) was used to integrate groundwater usage with irrigation. In these watersheds, pumped groundwater was used in addition to surface water withdrawals to satisfy the irrigation water quantity requirements. In several cases elsewhere in the Sacramento River watershed, the demand for irrigation water calculated based on the number of cultivated acres within the irrigation district boundary exceeded the supply of irrigation water. Irrigation withdrawals were increased to meet the water demands of the cultivated land within the irrigation district boundary. These cases are identified in Table 1.8, where "calculated from demand" is entered in the data available column. The processes governing irrigation water drainage within WARMF are identical to the precipitation – infiltration – runoff processes. Irrigation water that is applied to the land surface is utilized by the land cover types according to the prescribed water uptake rate. Surplus water will infiltrate into the soil layers, replenishing soil moisture and flowing both horizontally and vertically through the soil column according to the prescribed soil layer hydraulic conductivities. If saturation moisture levels are achieved, water will flow into the stream network via overland flow processes.

2 MODEL CALIBRATION

Procedure

Given meteorological and operational data, the Sacramento River Model made predictions for stream flow and water quality at various river segments. At locations where monitoring data was collected, the model predictions should match the measured stream flow and water quality. Some of the WARMF model coefficients such as slope, aspect, and other physical properties of the watershed are known. Other coefficients were initially left at default or typical literature values. The initial predictions made did not necessarily match the observed values very well. Model calibration was performed by adjusting model coefficients within reasonable ranges to improve the match between model predictions and observed data.

The model predictions and observed data were compared graphically. In the graph, the time series of model predictions were plotted in a curve on top of measured data. If the observed values fell on top of the curve, the match could be determined as good or poor by visual inspection.

The model predictions and observed data were also compared statistically. The differences between the predicted and observed values are errors. The magnitudes of the errors were calculated in the statistical terms of relative error, absolute error, root mean square error, and correlation coefficient. The relative (E_r) and absolute (E_a) errors are the primary statistics used in model calibration and are described as follows:

$$E_r = \frac{\sum (simulated - observed)}{n}$$

$$E_a = \frac{\sum | simulated - observed |}{n}$$

The error of each instance where there are both simulation results and observed data is the simulated minus the observed. The relative error cancels out errors greater than and less than observed and is thus a measure of model accuracy or bias. The absolute error measures model precision. Both can be expressed as a percent by dividing by the average observed value.

Both graphical and statistical comparisons were made with WARMF. WARMF has a scenario manager, where each scenario is a set of model input coefficients and corresponding simulation results. Scenario 1 may be used to represent a set of model coefficients used in the simulation. Scenario 2 may be used to represent an alternate set of model coefficients. After the simulations are complete, WARMF can plot the observed data as well as the model predictions for both scenarios on the same graph. By visual inspection, it is relatively easy to see whether the changes to model coefficients improve the match.

Likewise, WARMF calculates the values of various error terms for the model predictions. The comparison of the numerical values of errors for two scenarios can lead the user to adjust the model coefficients in the right direction to reduce the errors.

Model calibration followed a logical sequence. Hydrological calibration was performed first, because an accurate flow simulation is a pre-requisite for accurate water quality simulation. The calibrations for temperature, suspended sediment, turbidity, and conservative substances were performed before the calibration of nutrients (phosphate, ammonia, and nitrate), algae and dissolved oxygen concentrations.

Only a few model coefficients were adjusted for each calibration. For hydrological calibration, the boundary river inflows were checked for their accuracy as discussed in Chapter 1 of this report. Evapotranspiration coefficients, soil thickness, field capacity, saturated moisture, and hydraulic conductivity were then adjusted so that the simulated runoff from catchments could account for flow in headwater tributaries and thus for increases in flow between the monitoring stations along the mainstem of the major rivers within the model domain. For water quality calibration, coefficients used for model calibration include reaction rates, initial concentrations in the soil, and properties of each land use such as productivity. If the model does not match observed data after adjusting model coefficients, an investigation may find another cause of the mismatch, such as a diversion or point source missing from the model.

Model Coefficients

There are thousands of model coefficients in the Sacramento River WARMF model, including chemical reaction rates, soil depths and hydraulic conductivities, soil mineral compositions, temperature correction factors (to dynamically adjust reaction rates for temperature changes), and many others. Some apply throughout the watershed (referred to as "system coefficients"), some apply to individual land uses wherever they occur, and other coefficients apply to individual catchments and river segments. Many of the coefficients do not have a significant impact on simulation results and therefore could be safely left at default literature values unless there was location-specific information to enter. Coefficients to which the model is more sensitive had to be calibrated. WARMF contains default values of those parameters, which were used as the initial values for the model. These initial values were adjusted during the model calibration process in order to better match the simulations of stream flow and water quality with observations. The model coefficients that were calibrated are described in more detail in the following sections.

System Coefficients

The system coefficients (i.e. those that apply to the entire system) can be viewed by double-clicking on the white space on the WARMF map. For the Sacramento River model, evaporation-related coefficients were calibrated while other system coefficients relating to hydrology, such as snow melt rates, were left at default values. Table 2.1 lists the evaporation coefficients, along with the typical ranges within which the coefficients vary. The last column is the value used for the Sacramento River calibration.

Table 2.1 Calibrated System Coefficients

Coefficient	Units	Description	Range	Value
Evaporation Magnitude	None	Multiplier of potential evapotranspiration calculated from temperature, humidity, and latitude	0.6 – 1.4	1
Evaporation Skewness	None	Seasonal adjustment of evapotranspiration calculations	0.6 – 1.4	1

There are a number of model system coefficients which have values for each land use. These coefficients define how the different land uses receive anthropogenic model inputs such as irrigation and respond to natural model inputs such as atmospheric deposition. These coefficients are accessed in WARMF the same way as the coefficients above, by double-clicking in the white space on the WARMF map. These were set based on literature values and agricultural practice. The land use coefficients are under the land use tab of the ensuing dialog box. The model is sensitive to the coefficients shown in Table 2.2.

Table 2.2 Calibrated System Land Use Coefficients

	Impervious Fraction	Cropping Factor	Productivity	Leaf Area Index
Units	none	none	kg/m2/yr	none
Description	Portion of each land use which is paved	"C" factor of Universal Soil Loss Equation[1]	Net creation of vegetation	Ratio of leaf area to land area[1]
Range	0 - 1	0 - 1	0 – 4	0-13
Barren land	0	1	0	0
Cotton	0	0.5	0.06	1.0
DairyPA	0	0.5	0	1.0
Deciduous Forest	0	0.0055	0.8	1.0
Double Crop DLA	0	0.5	3.14	1.0
Evergreen Forest	0	0.01	0.8	13.0
Fallow	0	0.1	0.1	1.5
Farmsteads	0.10	0.2	0.27	0.4
Flowers and nursery	0	0.5	2.02	1.0
Grassland/Herbaceous	0	0.075	0.1	1.5
Lagoon	0	0	0	0
Marsh	0	0	0.8	1.5
Mixed Forest	0	0.01	0.8	7.0
Native Classes Unsegregated	0	0.01	0.3	1.0
Olives, citrus & subtropicals	0	0.1	2.02	1.0
Orchard	0	0.1	0.67	1.0
Other CAFOs	0.15	1	0	0
Other row crops	0	0.5	1.34	1.0
Paved areas	1.00	0	0	0
Perennial forages	0	0.1	1.57	1.5
Perennial Forages DLA	0	0.5	1.57	1.0
Rice	0	0.01	0.90	1.0
Sewage plant incl. ponds	0.95	0	0	0
Shrub/Scrub	0	0.075	0.3	1.5
Urban Commercial	0.80	0.5	0.22	1.0
Urban Industrial	0.90	0.5	0.22	1.0
Urban landscape	0.20	0	0.27	0
Urban residential	0.15	0.125	0.27	0.4
Vines	0	0.1	0.40	1.0
Warm season cereals/forages	0	0.5	2.02	1.0
Water	0	0	0	0
Winter grains & safflower	0	0.5	1.12	1.0

[1] These coefficients vary by month. Coefficients for May are shown for illustrative purposes.

Catchment Coefficients

Catchment coefficients are the coefficients that apply to individual catchments throughout the modeled watershed area. These coefficients are important for simulating shallow groundwater flow and nonpoint source load. They can be set to different values for each catchment if they have different properties or lumped together with the same values. The coefficients for each individual catchment can be viewed and edited in WARMF by double-clicking on a catchment.

The catchment area, slope, and aspect were calculated from digital elevation models and are not subject to calibration. Meteorology coefficients were calculated based on meteorology station data and high resolution gridded climate data (PRISM data) as described in Chapter 1. In a few cases where it was evident that the total volume of rainfall was consistently too high or too low, the precipitation multiplier was further adjusted during the calibration process. Land use percentages within each catchment were calculated by overlaying a land use shapefile with catchment boundaries. Fertilization and irrigation were estimated from agricultural practice as shown in Table 1.6 and Table 1.9. The remaining coefficients that required calibration were primarily soil properties and chemical reaction rates.

Calibration of the soil properties (listed in Table 2.3) is essential to adequately match the simulated with the observed quantity and timing of streamflow. Three soil layers were used in the Sacramento River application. These layers represent the shallow groundwater that interacts with surface waters, which is the focus of watershed modeling. Deep groundwater, which does not interact significantly with surface waters, is not included in the model. The Sacramento River WARMF application includes 479 individual catchments. However, observed streamflow data was not available at the outlet of every catchment. Therefore streamflow calibration was performed only where observed data was available. In particular, calibration efforts were focused on headwater tributaries where local area runoff is the sole source of streamflow and the impacts of soil coefficient adjustments are greatest. In catchments further downstream or below a reservoir, inflow to the river is much larger than local shallow groundwater runoff. Thus the effects of coefficient adjustments are diluted. In cases where multiple catchments were located upstream of a tributary streamflow station, the soil coefficients of all upstream catchments were assigned the same values and calibrated together.

Table 2.3 Calibrated Catchment Soil Coefficients

Coefficient	Units	Range
Layer 1 thickness	cm	> 0
Layer 2 thickness	cm	> 0
Layer 3 thickness	cm	> 0
Layer 1 field capacity	none	0.1-0.3
Layer 2 field capacity	none	0.1-0.3
Layer 3 field capacity	none	0.1-0.3
Layer 1 saturation moisture content	cm	0.2-0.5
Layer 2 saturation moisture content	cm	0.2-0.5
Layer 3 saturation moisture content	cm	0.2-0.5
Layer 1 initial moisture content	none	0.1-0.5
Layer 2 initial moisture content	none	0.1-0.5
Layer 3 initial moisture content	none	0.1-0.5
Layer 1 Horizontal hydraulic conductivity	cm/d	> 0
Layer 2 Horizontal hydraulic conductivity	cm/d	> 0
Layer 3 Horizontal hydraulic conductivity	cm/d	> 0
Layer 1 Vertical hydraulic conductivity	cm/d	> 0
Layer 2 Vertical hydraulic conductivity	cm/d	> 0
Layer 3 Vertical hydraulic conductivity	cm/d	> 0
Layer 1 Root distribution (fraction) reaching the layer	none	0.0 - 1.0
Layer 2 Root distribution (fraction) reaching the layer	none	0.0 - 1.0
Layer 3 Root distribution (fraction) reaching the layer	none	0.0 - 1.0

Reaction rates are important coefficients for water quality simulations. The reaction rates of most significance for the Sacramento River model are shown in Table 2.4. These rates are dynamically adjusted during the simulation based on changes in temperature. Reactions only occur under the proper dissolved oxygen concentration, for example nitrification under oxic conditions and denitrification when dissolved oxygen is near zero.

Table 2.4 Important Catchment Reaction Rate Coefficients

Reaction Rate	Units	Range	Value
BOD Decay	1/d	0.05-0.5	0.1
Organic Carbon Decay	1/d	0-0.1	0.001
Nitrification	1/d	0-0.1	0.001
Denitrification	1/d	0-0.1	0.1
Sulfate Reduction	1/d	0-0.5	0.05

The other important parameters for calibrating the water quality of the shallow groundwater include the initial concentrations of each chemical constituent in each soil layer of each catchment (Table 2.5). The initial concentrations weren't calibrated, but were set based on a balance over the course of the simulation. The initial concentrations were set individually for each catchment and soil layer to match the ending concentrations of the simulation under the assumption that the actual soil chemistry in the Sacramento Valley is in relative equilibrium rather than undergoing a trend of increasing or decreasing concentration.

Table 2.5 Catchment Initial Soil Pore Water Concentrations

Constituent	Units	Values
Ammonia	mg/l as N	0.02-2
Calcium	mg/l	10-60
Magnesium	mg/l	4-60
Potassium	mg/l	0.5-5
Sodium	mg/l	2.5-230
Sulfate	mg/l	1-330
Nitrate	mg/l as N	0.01-8
Chloride	mg/l	0.1-130
Phosphate	μg/l as P	100-1000
Organic Carbon	mg/l	1-8
Dissolved Oxygen	mg/l	0.1-8

River Coefficients

Physical data for river segments, including upstream and downstream elevations and lengths, are derived from digital elevation model data. Default stage-width curves and roughness coefficients (i.e. Manning's n) were used for each river segment since no travel time or survey data were available to populate these values. A Manning's n value of 0.04 was used as recommended by Rosgen (1996). Default values were also used for reaction rates and river bed scour coefficients. Table 2.6 shows the reaction rates.

Table 2.6 River Reaction Rate Coefficients

Reaction Rate	Units	Range	Value
BOD Decay	1/d	0.1-1	0.2
Organic Carbon Decay	1/d	0.01-0.1	0.07
Nitrification	1/d	0.01-1	0.5
Denitrification	1/d	0-1	0
Sulfate Reduction	1/d	0-0.5	0
Clay Settling	m/d	>0	0.000346
Silt Settling	m/d	>0	8.64
Sand Settling	m/d	>0	1036.8
Diatom Growth	1/d	0.2-0.5	3.2
Diatom Respiration	1/d	0.1-0.5	0.15
Diatom Mortality	1/d	0.1-0.5	0.05
Diatom Settling	m/d	0-1	0
Detritus Decay	1/d	0-1	0.2
Detritus Settling	m/d	0-1	0
Settled Detritus Decay	1/d	0-0.1	0.2

In addition to the settling rates shown above Sediment transport in rivers is affected by scour from the river bed. Scour is controlled by the shear velocity of the water next to the river bed. Above the critical shear velocity, scour is calculated in the form aV^b. The values of coefficients ‘a’ and ‘b’ were calculated using a subset of the continuous TSS monitoring dataset collected at the Sacramento River at Freeport. Since stream TSS concentrations are the result of both scour and overland erosional processes, optimization of these coefficients was accomplished by selecting TSS samples from the Freeport TSS dataset that were collected during periods when overland flow was insufficient for sediment transport, but river flow velocities were fast enough to scour the river bed. Coefficients ‘a’ and ‘b’ were optimized by minimizing the difference between simulated and observed TSS concentration during scour-dominated periods. For all river segments in the Sacramento River WARMF model, $a=1.0 \times 10^{-6}$ and b=1.3. The WARMF sediment transport simulation is dependent upon extensive TSS data collection. Establishing additional continuous monitoring stations within the watershed would be valuable for calibrating the model at upstream locations and could be used to improve the WARMF TSS and turbidity simulation algorithms.

Adsorption coefficients control the partitioning between the dissolved phase of each constituent and the portion adsorbed to suspended sediment. For ammonia and phosphate, the adsorption isotherms were calculated using concurrent data of suspended sediment with ammonia, nitrate, and total nitrogen for the ammonia isotherm, and phosphate and total phosphorus for the phosphorous isotherm. Although calculated values varied greatly based on location and sample date, median values were determined (Table 2.7) and applied uniformly to all river segments. Default isotherms were used for all other constituents.

Table 2.7 Adsorption Isotherm Coefficients

Constituent	Units	Values
Ammonia	L/kg	1,400,000*
Calcium	L/kg	472.552
Magnesium	L/kg	404.556
Potassium	L/kg	197.971
Sodium	L/kg	20.7365
Sulfate	L/kg	16.2596
Nitrate	L/kg	0
Chloride	L/kg	0
Phosphate	L/kg	200,000*
Organic Carbon	L/kg	107.184
EC (Conservative)	L/kg	0

* Calculated from concurrent data, all others default values (no concurrent data was available)

Hydrologic Calibration

Hydrologic calibration is the process of adjusting the coefficients of the rainfall-runoff model within WARMF so that the simulations of streamflow match the observations as well as possible. There are three levels of hydrologic calibration: global, seasonal, and event. Global calibration is the process of matching the simulated annual volume of water passing a gage to the volume measured at the gage. In seasonal calibration, the simulated seasonal variation of streamflow is compared and adjusted to follow the same pattern on a measured hydrograph (i.e., a graph of streamflow rising and falling over time). The measured hydrograph typically has a period of high flow during the rainfall season and a recession to base flow during the dry season. Event calibration is the process of matching the simulated peak flows to the observed peaks during precipitation events.

There were 37 streamflow gaging stations on headwater tributaries within the Sacramento River WARMF model domain where simulated flow could be compared to observed data for model calibration. Eleven of these stations are located within the east side tributaries region of the model domain and are listed below in Table 2.8.

Table 2.8 East Side Tributaries Streamflow Stations and Calibrated Catchments

Gaging Station	Tributary catchment	Period of Record
Camp Creek near Somerset	Camp Creek	1954-2004
South Fork Cosumnes River near River Pines	Cosumnes River	1957-1980
North Fork Cosumnes River near El Dorado	Cosumnes River	1911-1987
Cosumnes River at Michigan Bar	Cosumnes River	1907-2010
Deer Creek near Sloughhouse	Deer Creek	1960-1977
Cosumnes River at McConnell	Cosumnes River	1941-1982
Dry Creek near Galt	Dry Creek	1926-1997
Mokelumne River at Woodbridge	Mokelumne River	1924-2009
Bear Creek near Lockeford	Bear Creek	1930-1985
Mokelumne River below Camanche Dam	Mokelumne River	1904-2010
Calaveras River below New Hogan Dam	Calaveras River	1961-2010

Some representative calibration results are shown in Figure 2-1 through Figure 2-4 below. Simulation results are shown in blue lines and observed data in black circles. Ideally, the blue lines pass through all the black circles. However this is unlikely to occur due to a combination of model error, meteorology error, database error, and stream discharge measurement error. During the calibration process, coefficients were adjusted so that large systematic differences were removed and an overall balance was achieved between positive and negative errors (i.e. simulations were not consistently too high or too low indicating that differences are due primarily to random errors in data rather than coefficient values).

In addition to visual inspection, statistical error measurements were used to evaluate how well the simulated matched the observed (under the assumption that the observations are error-free). The three primary statistics used were relative error, absolute error and R squared. Relative error is the average of the deviations between simulated and observed. Absolute error is the average of the absolute differences between model predictions and observations. R squared is the coefficient of determination or the square of the correlation coefficient. Relative error was the primary statistic used in calibration because a low relative error is indicative of a good water balance. Simulating the correct quantity of water is important in determining the sources of pollutants including turbidity and organic carbon. In rivers with highly variable flow, the R squared statistic is higher with correct timing of peak flows. While the primary concern for drinking water is often long-term pollutant load irrespective of timing, in this case timing of turbidity is important since it impacts the presence of Delta Smelt in the vicinity of Delta drinking water intakes. The R squared statistic must be evaluated in conjunction with the other statistics. If the model were simulating exactly twice as much flow as observed, R squared would be very high but the calibration would be very poor because it would not have a water balance. Statistics for flow calibration at Camp Creek near Somerset, Cosumnes River at Michigan Bar, Mokelumne River at Woodbridge, and Dry Creek at Galt are shown in Table 2.9 below. The stations were selected from the larger suite of observed data locations because they are representative of the range of hydrologic conditions present within the study area. Because the objective of the project was to produce an analytical model capable of predicting flow, organic carbon concentration, and turbidity at the mouth of each of the east side tributaries, calibration of the other chemical concentrations simulated by WARMF is coarse. Further calibration could be used to increase model accuracy for nutrients and major cations (presenting results for all chemical constituents is beyond the scope of this report. The results can be reviewed in the WARMF model output).

In the figures below, calibration results as well as differences in hydrologic characteristics are evident between watersheds. In the mountainous headwaters (e.g. Camp Creek), a consistent pattern of significant seasonal runoff is evident and is generally well simulated by the model. Baseflow drops to near zero but continues in this and other similar catchments during the dry season, with few or no peaks. Hydrograph peaks in Camp Creek are generally well-simulated, with errors distributed between over and under-simulation. Errors are likely attributable in large part to error in model input caused by the sparse coverage of meteorology stations across the model domain.

In the lower elevation, drier headwater watersheds (e.g. Dry Creek) the seasonal pattern of runoff is much less consistent from year to year with longer periods of low to zero baseflow. Drier watersheds are typically more difficult to simulate due to the larger impact of data errors, high spatial variability within the watershed, and the occurrence of complex hydrologic processes (e.g. Hortonian runoff). Figure 2-4 below demonstrates that the seasonal pattern of runoff is well captured but large errors occur in the simulation of peaks. These errors have a greater impact on the calibration statistics in these watersheds since the total volume of flow is lower (i.e. the ratio of error to mean flow is higher).

In watersheds downstream of major reservoirs (e.g. Mokelumne River at Woodbridge), flow is dominated by reservoir outflow. The impact of runoff from the local watershed, and therefore the impact of coefficient adjustments, is much lower than in the headwater watersheds. Calibration statistics are generally very good in these watersheds reflecting the fact that the volume of streamflow is primarily reservoir outflow, which is a known quantity. The case is surely similar for the Calaveras River, since New Hogan Reservoir discharge contributes the majority of stream flow in this system. Therefore, while there isn't observed stream discharge data collected in the vicinity of the Calaveras River mouth, simulation results for this system are likely to be extremely accurate.

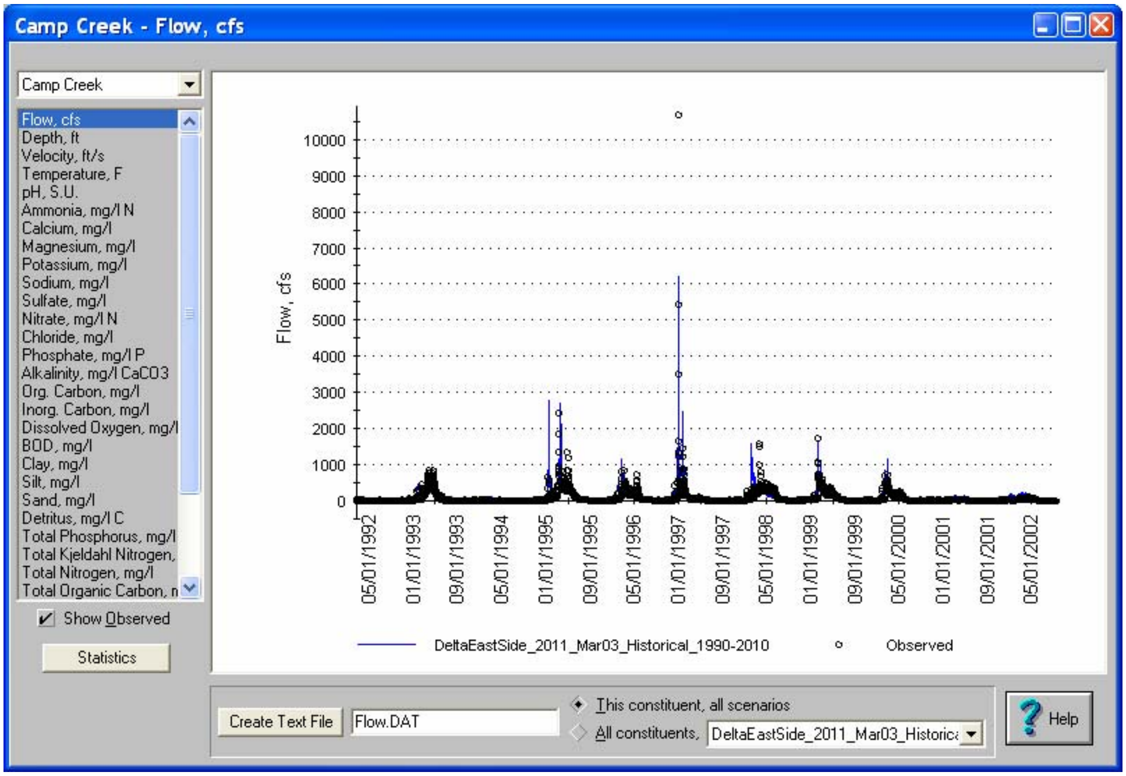

Figure 2-1 Simulated vs Observed Flow at Camp Creek near Somerset

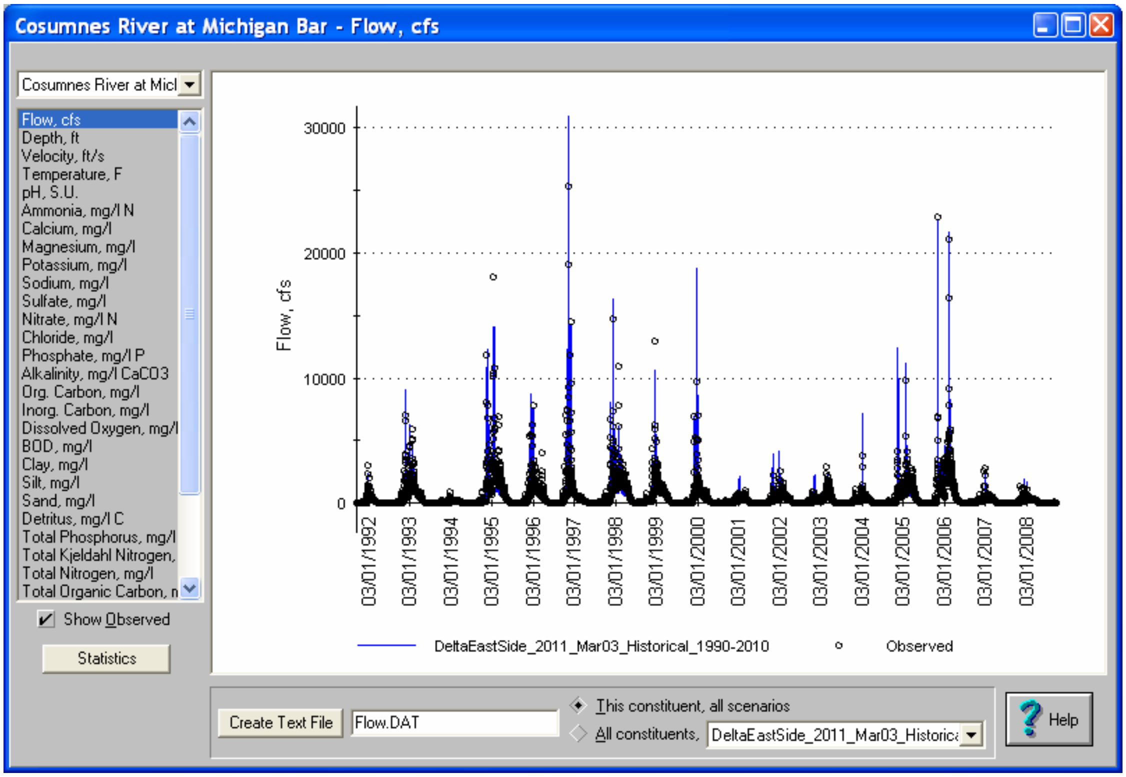

Figure 2-2 Simulated vs Observed Flow at Cosumnes River at Michigan Bar

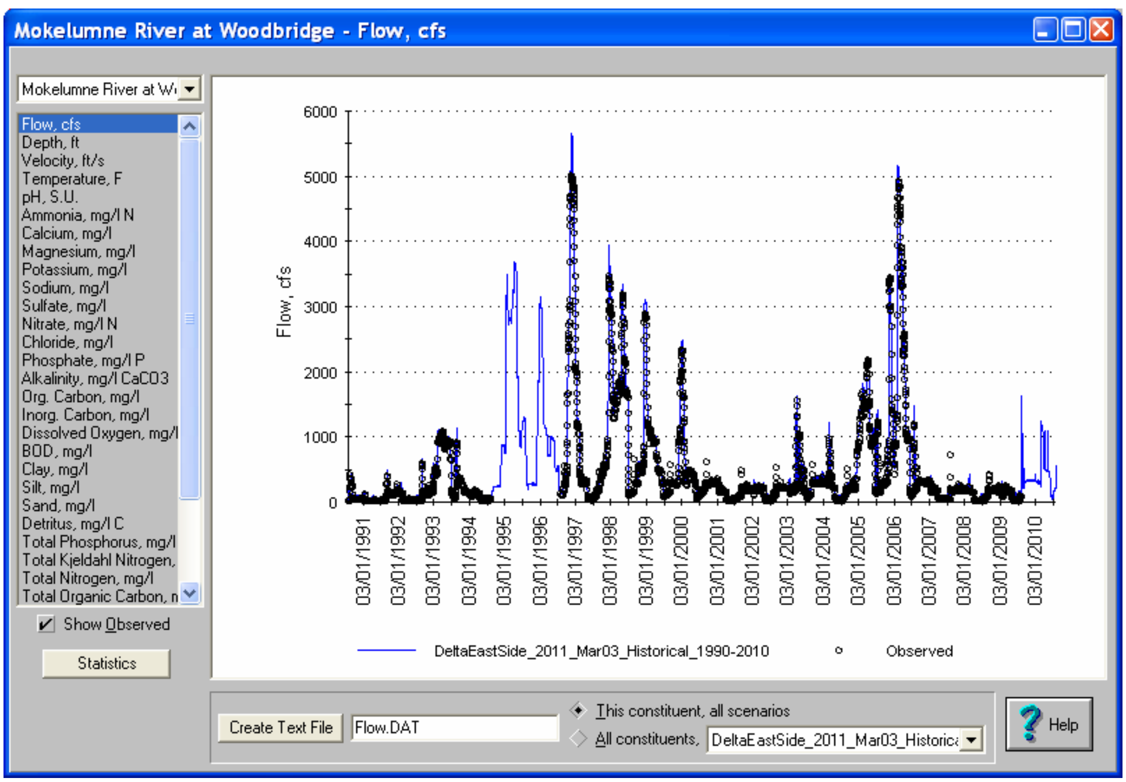

Figure 2-3 Simulated vs Observed Flow at Mokelumne River at Woodbridge

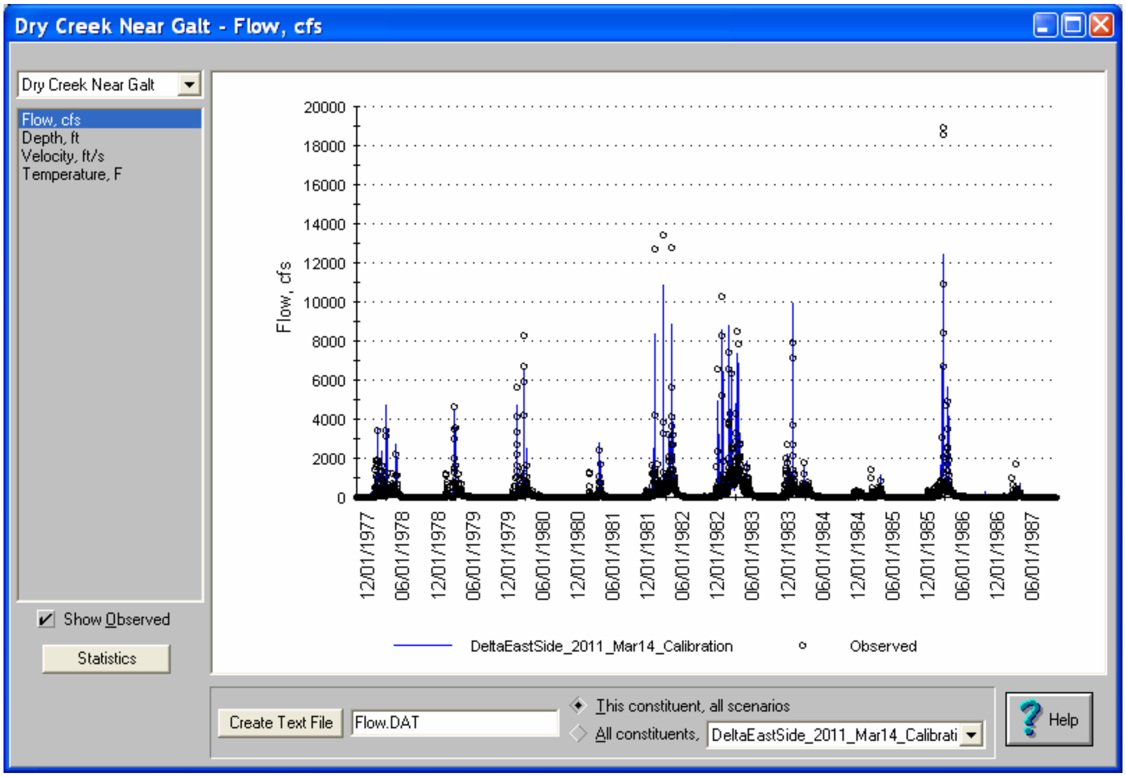

Figure 2-4 Simulated vs Observed Flow at Dry Creek near Galt

Table 2.9 Flow Calibration Statistics for East Side Tributaries Locations

Gaging Station	Measured Time Period	% Relative Error	% Absolute Error	R squared
Camp Creek near Somerset	1990-2010	20.0	60.2	0.598
Cosumnes River at Michigan Bar	1990-2010	1.1	45.4	0.756
Mokelumne River at Woodbridge	1980-1990	9.6	10.7	0.993
Dry Creek at Galt[1]	1977-1987	2.7	40.9	0.855

[1]The most recent ten year period of continuous observed stream discharge was used to calibrate

Water Quality Calibration

After the hydrologic calibration, water quality calibration was performed. As stated in the scope of work, the objective of this effort is to develop a watershed model capable of simulating organic carbon and turbidity fluxes to the Sacramento – San Joaquin River Delta from the east side tributaries. Given this objective the water quality calibration followed a certain order, reflecting the interdependence between water quality constituents (e.g. turbidity is calculated from total suspended sediment, which affects organic carbon concentration). Generally, total suspended sediment was calibrated first, followed by organic carbon.

Water quality data were collected at twenty-five different locations in the east side tributaries region of the Sacramento River WARMF simulation. The locations of all the water quality sites located within the east side tributaries region are illustrated with white circles in Figure 2-5. Eighteen of these locations were used to set the initial soil cation and anion concentrations, adjust soil mineral content for each catchment, and to calibrate the WARMF simulation. These stations, along with the time periods during which in-stream water chemistry data were collected are listed in Table 2.10. Calibration was not specifically performed for all of the listed sites. Calibration results from a subset of these water quality data collection stations are presented in the following sections. These sites were selected from the larger set of stations based on their geographic location within the watershed, the number of samples collected for each of the parameters of interest, and to illustrate WARMF simulation capabilities under a variety of land use patterns (e.g. predominantly agricultural watersheds, upland tributaries, etc.).

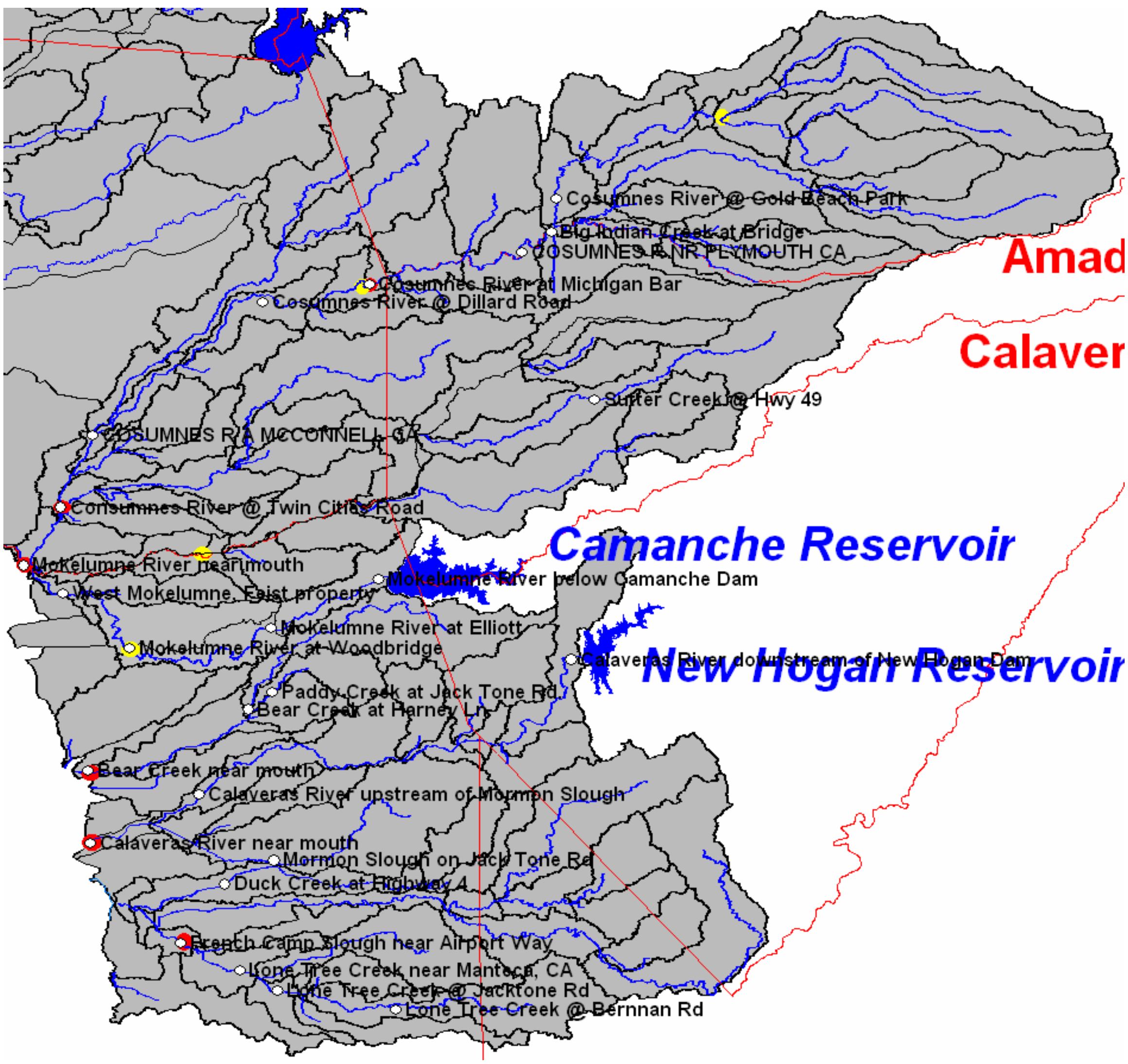

Figure 2-5 Locations of Water Quality Monitoring Stations

Table 2.10 East Side Tributaries Water Quality Monitoring Stations

River	Location	WARMF Subwatershed	Water Chemistry Data Collection Period(s)			
			Begin	End	Begin	End
Cosumnes River	Gold Beach Park	Cosumnes River at Michigan Bar	2002	2002		
Cosumnes River	Plymouth		2002	2002		
Cosumnes River	Michigan Bar		1952	1980	2001	2006
Cosumnes River	Dillard Road	Cosumnes River at Mouth	1983	1984		
Cosumnes River	McConnell		1960	1967		
Cosumnes River	Twin Cities Road		1998	2006		
Sutter Creek	Highway 49 Bridge	Dry Creek	2002	2002		
Mokelumne River	Elliott	Mokelumne River	2000	2005		
Mokelumne River	Woodbridge		1983	1984		
West Mokelumne	Feist Property		1997	2005		
Mokelumne River	At River Mouth		1997	2010		
Bear Creek	At River Mouth	Bear Creek	2000	2007		
Calaveras River	Upstream of Mormon Slough	Calaveras River	2000	2007		
Mormon Slough	Jack Tone Road		2004	2006		
Calaveras River	At River Mouth		2008	2010		
Lone Tree Creek	Jack Tone Road	French Camp Slough	2004	2006		
French Camp Slough	Airport Way		1962	1967	2000	2006
Lone Tree Creek	Manteca		1960	1967	2000	2004

The following sections describe the calibration results for the water quality parameters of interest at a selection of the sites listed in Table 2.10. For each water quality parameter, the simulated results (blue lines) and observed data (black circles) are compared from the most upstream station to the most downstream station. Additional water quality calibration results for the remainder of the Sacramento River WARMF model domain are available for review in a separate report produced for the California Urban Water Agencies titled, *Task 3 Technical Memorandum - Analytical Modeling of the Sacramento River* (Systech Water Resources, Inc., 2011).

Turbidity

Differences between observed and simulated water turbidity were analyzed at seven locations within the east side tributaries region of the Sacramento River WARMF model domain. These locations include Cosumnes River at Michigan Bar, Cosumnes River at Twin Cities Road, Mokelumne River at Elliott, Mokelumne River at mouth, Bear Creek near mouth, Calaveras River near mouth, and French Camp Slough at Airport Way. Figure 2-6 through Figure 2-12 illustrate the results of the calibration efforts.

Table 2.11 shows the model errors for turbidity at the selected monitoring stations within the east side tributaries region of the Sacramento River WARMF model domain. As mentioned in the background section of this report, Delta Smelt tend to favor higher turbidity conditions during their upstream winter spawning migration. The Smelt can be caught in Delta drinking water facility pumps when high turbidity conditions exist in the vicinity of the pumps at the right time of year. Protection of the endangered Delta Smelt is the primary motivation for simulating turbidity in the east side tributaries. Therefore, the WARMF calibration for turbidity emphasized timing rather than magnitude of turbidity flux to ensure that "muddy" water occurred at the correct time of year. The r-squared statistic is the most appropriate of the three WARMF model performance metrics to use in evaluating the timing of simulation results. The percent relative error was also minimized where possible without reducing the r-squared value.

Visual inspection of Figure 2-6 through Figure 2-9, and Figure 2-11 indicates that the model is performing well in the Cosumnes, Mokelumne, and Calaveras River watersheds with respect to the timing of turbidity peaks. The WARMF model simulation results tend to diverge from the observations during low flow periods. This is most evident in Figure 2-11. Between April 2009 and January 2010, simulated turbidity decreases from approximately 18 NTU to approximately 1 NTU while the observed data pattern remains relatively consistent, fluctuating between 3 and 17 NTU. While accurate turbidity simulation during the summer/low flow time period is not critical with respect to Delta Smelt preservation, the majority of the simulation error is likely due to the current method used to estimate turbidity in WARMF. WARMF currently calculates turbidity based on the simulated silt and clay concentrations in the river water column. Therefore, during periods of low flow, clay and silt settle out of the water column and the simulated turbidity decreases accordingly. In natural river systems turbidity is affected by factors in addition to suspended sediment concentration. Incorporating additional factors such as algae growth into the WARMF turbidity calculation may improve the low flow turbidity simulation results.

Figure 2-8 illustrates a near perfect fit between the simulated and observed turbidity values. The accuracy and precision of the model during this time period is a product of the boundary inflow file generation process. Data collected at the Mokelumne River at Elliott were used to populate the Camanche Reservoir boundary inflow file. The algorithms used to create the boundary inflow files utilize observed data when available, then estimate chemical concentrations at all other model time steps based on trends in the observed data. Therefore, the results shown in Figure 2-8 indicate that the boundary inflow file generation algorithms are functioning as intended.

There is a high degree of uncertainty associated with turbidity simulation results in the Bear Creek and French Camp Slough watersheds. Figure 2-10 and Figure 2-12 illustrate the simulation errors in these two watersheds respectively. It is difficult to identify the cause(s) of error in these watersheds due to a lack of observed turbidity information and the absence of observed discharge information. Calibrated hydrology coefficients from the Cosumnes watershed were used to simulate the hydrology in Bear Creek and French Camp Slough. It is reasonable to assume that watersheds in close proximity to one another will have similar soil and geologic characteristics, and will therefore respond similarly to precipitation inputs. However, it is impossible to assess the accuracy of this assumption without observed stream discharge information. The process of water quality calibration is greatly complicated by uncertainty in simulation hydrology. In both the Bear Creek and French camp slough watersheds, a variety of coefficients affecting sediment transport were adjusted in an attempt to improve the turbidity simulation results. The r-squared statistic could not be improved by adjusting the sediment transport coefficients. When the observed data are examined it becomes evident that turbidity in the Bear Creek and French Camp Slough watersheds does not follow the expected pattern of high values during the hydrologically active time periods (winter/spring) and low values during the dry seasons. The pattern present in the observed data indicates an opposite effect, with turbidity peaks occurring during the dry season. This indicates that sediment transport processes are not likely to be the dominant driver of turbidity levels in these watersheds. Tidal intrusion may be replacing water derived from local sources with Delta water. An in depth investigation of turbidity, algal biomass, agricultural runoff, and best management practices in these watersheds would be useful in determining the specific processes leading to the timing and magnitude of elevated turbidity levels. Although tidal processes can not be simulated by WARMF, the remaining information could be incorporated into WARMF to refine the turbidity prediction algorithms.

As part of this project, simulation of turbidity was added not just to the Delta east side tributaries but also to the San Joaquin River watershed WARMF application. The San Joaquin River was calibrated for suspended sediment concentration. A linear relationship was established between suspended sediment concentration and turbidity (turbidity (NTU) = 0.5311 * TSS (mg/l)) using concurrent data measured in the San Joaquin River at Vernalis. The simulated and observed turbidity at Vernalis are shown in Figure 2-13.

Note that there are two divergent measured data sources shown in Figure 2-13. In black circles is the continuous monitoring data collected by the California Data Exchange Center and reported as turbidity. In red triangles is the data collected by the US Geological Survey and reported as total suspended solids, multiplied by the San Joaquin River turbidity / suspended sediment ratio of 0.5311. The CDEC data does not appear to be reliable, at least in 2008, as it includes high peaks in summer when flow is low. The USGS data does not show corresponding peaks in sediment concentrations. The simulated turbidity at Vernalis follows the USGS data and the 2009-2010 CDEC data, but does not simulate peak levels observed in the USGS data in early 2008 or the peak in CDEC data in early 2010.

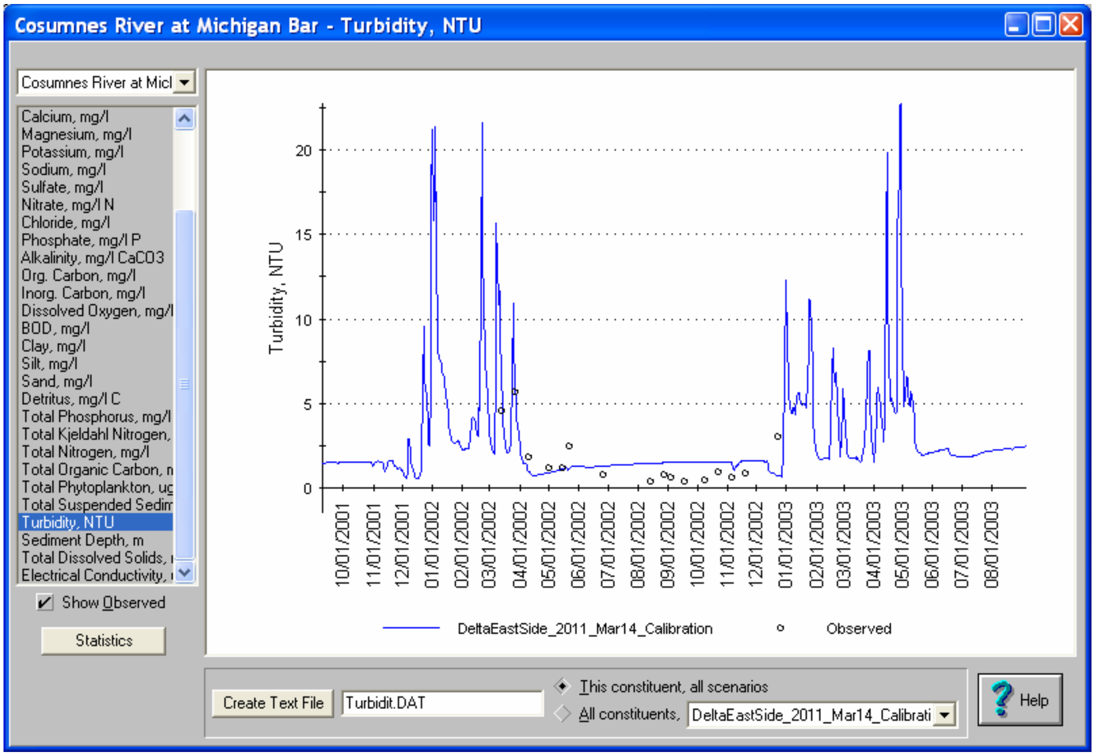

Figure 2-6 Simulated and observed Turbidity at Cosumnes River at Michigan Bar

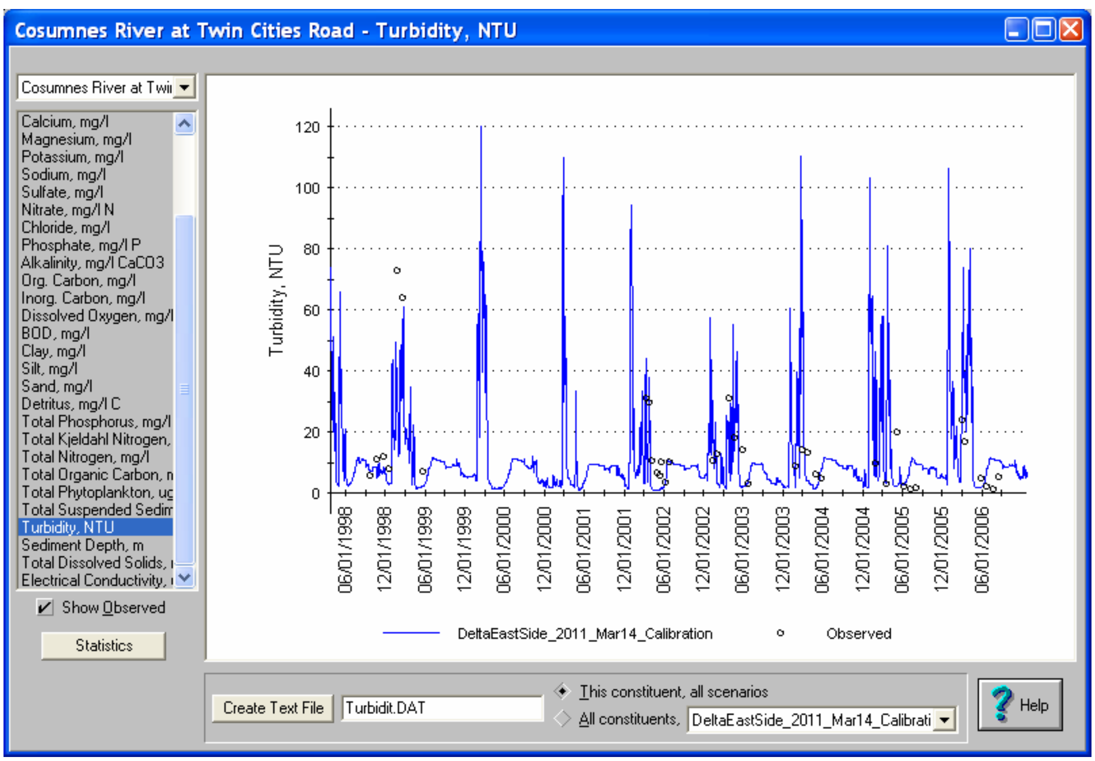

Figure 2-7 Simulated and observed Turbidity at Cosumnes River at Twin Cities Road

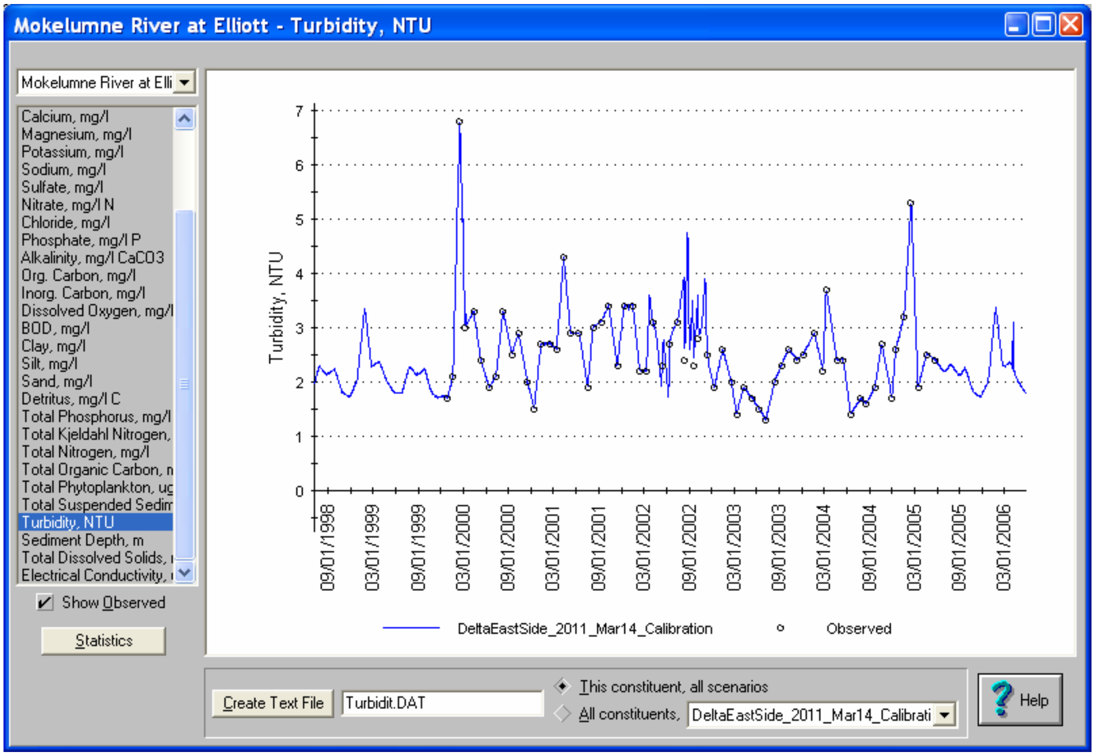

Figure 2-8 Simulated and observed Turbidity at Mokelumne River at Elliott

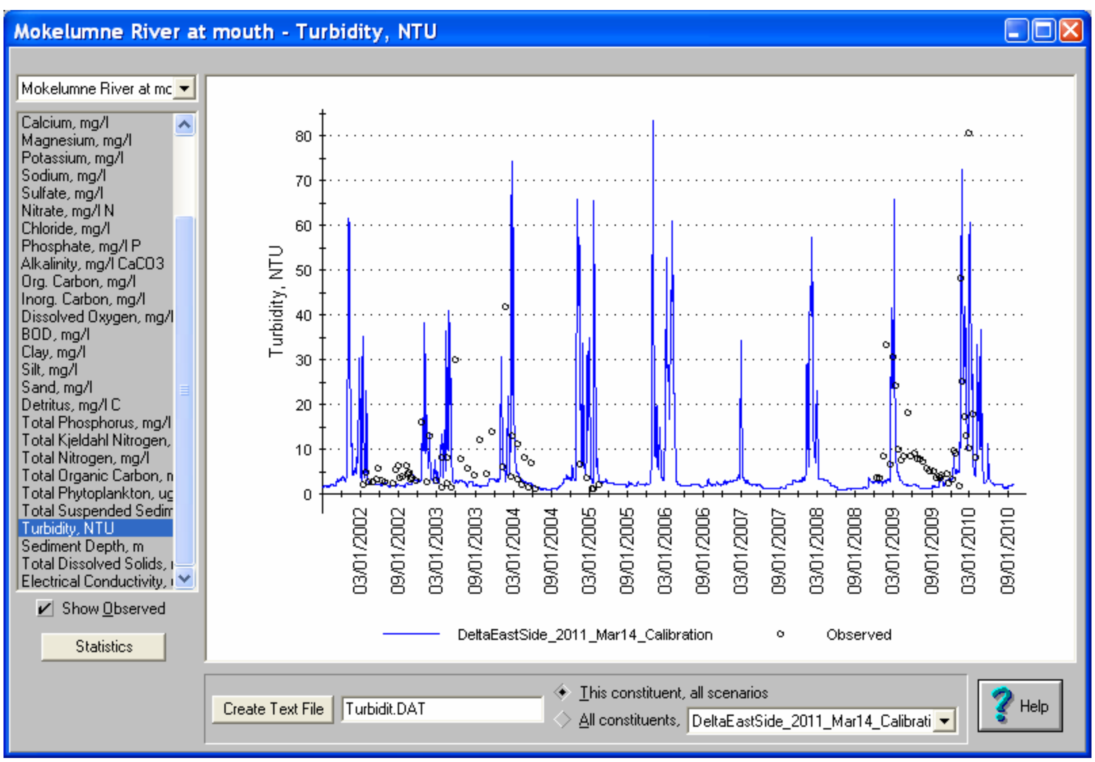

Figure 2-9 Simulated and observed Turbidity at Mokelumne River at mouth

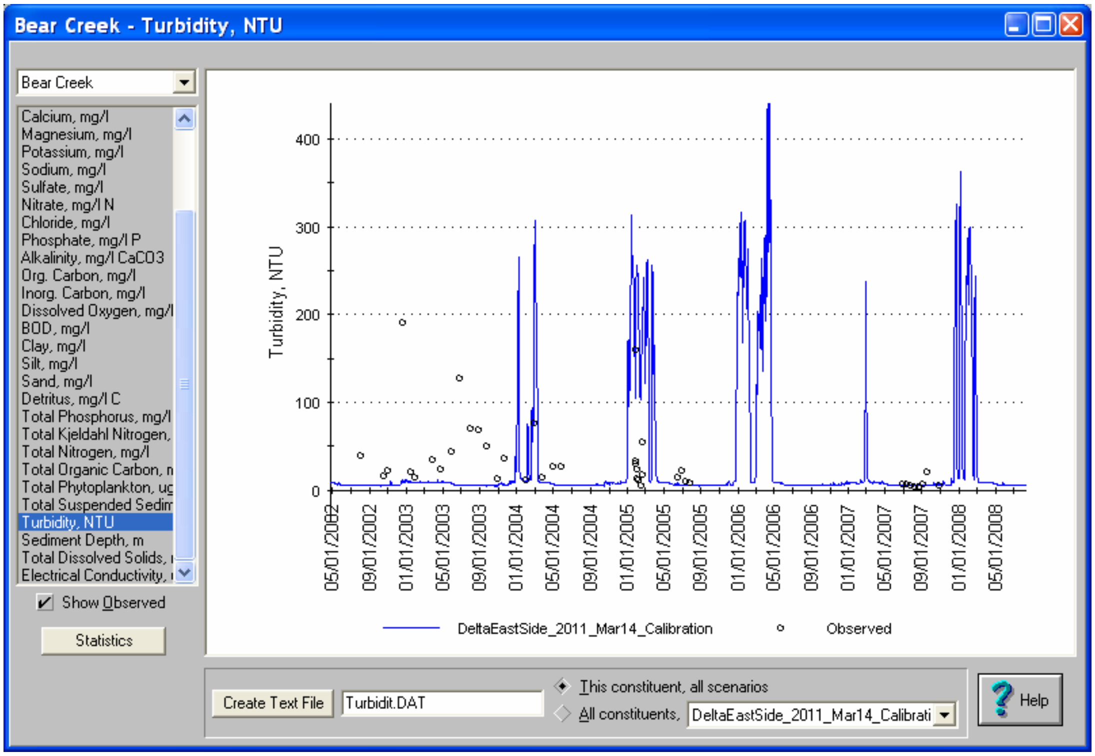

Figure 2-10 Simulated and observed Turbidity at Bear Creek near mouth

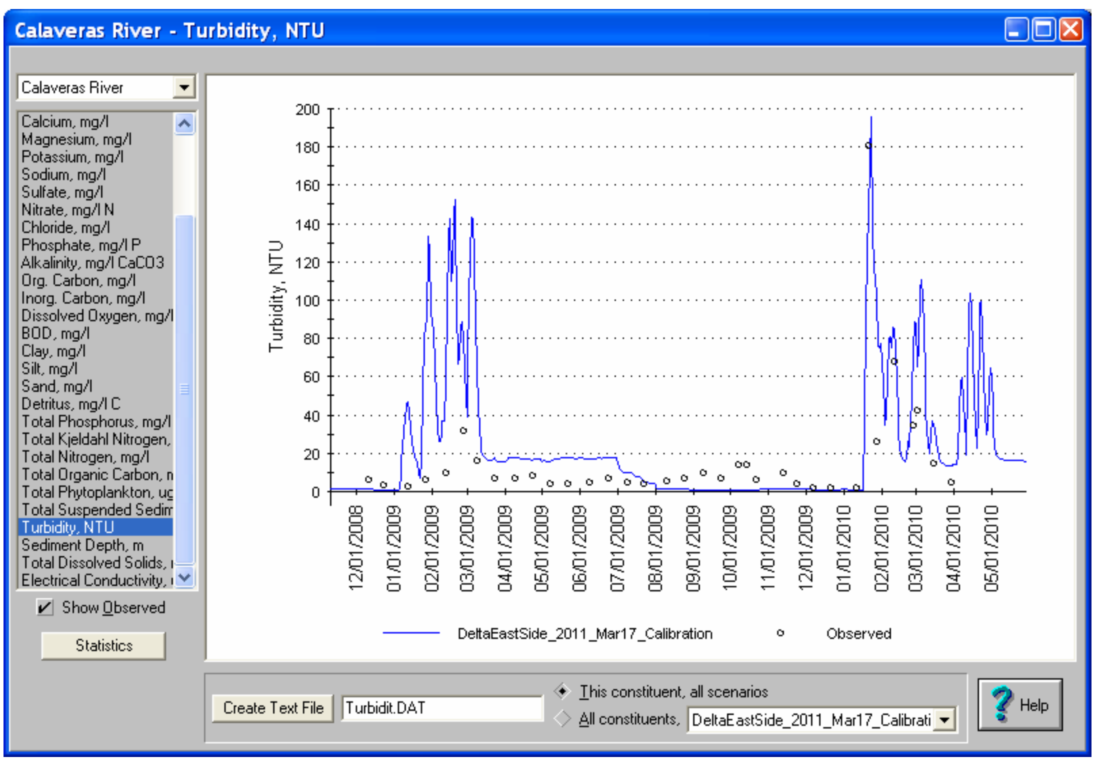

Figure 2-11 Simulated and observed Turbidity at Calaveras River near mouth

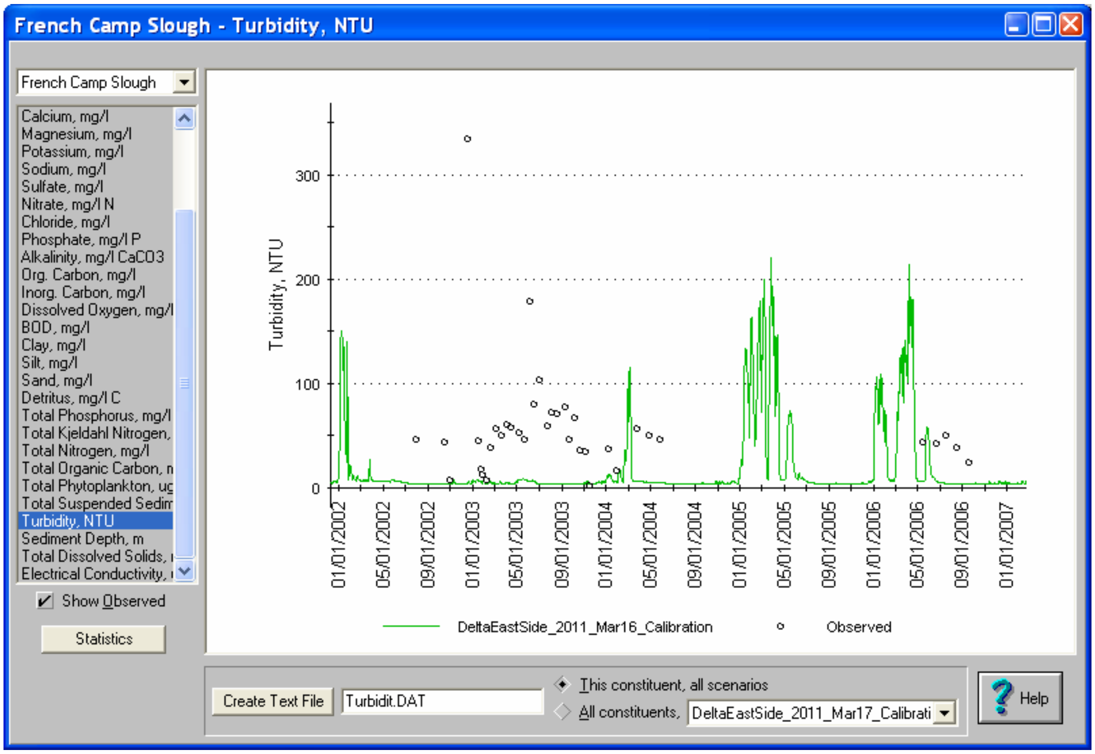

Figure 2-12 Simulated and observed Turbidity at French Camp Slough near Airport Way

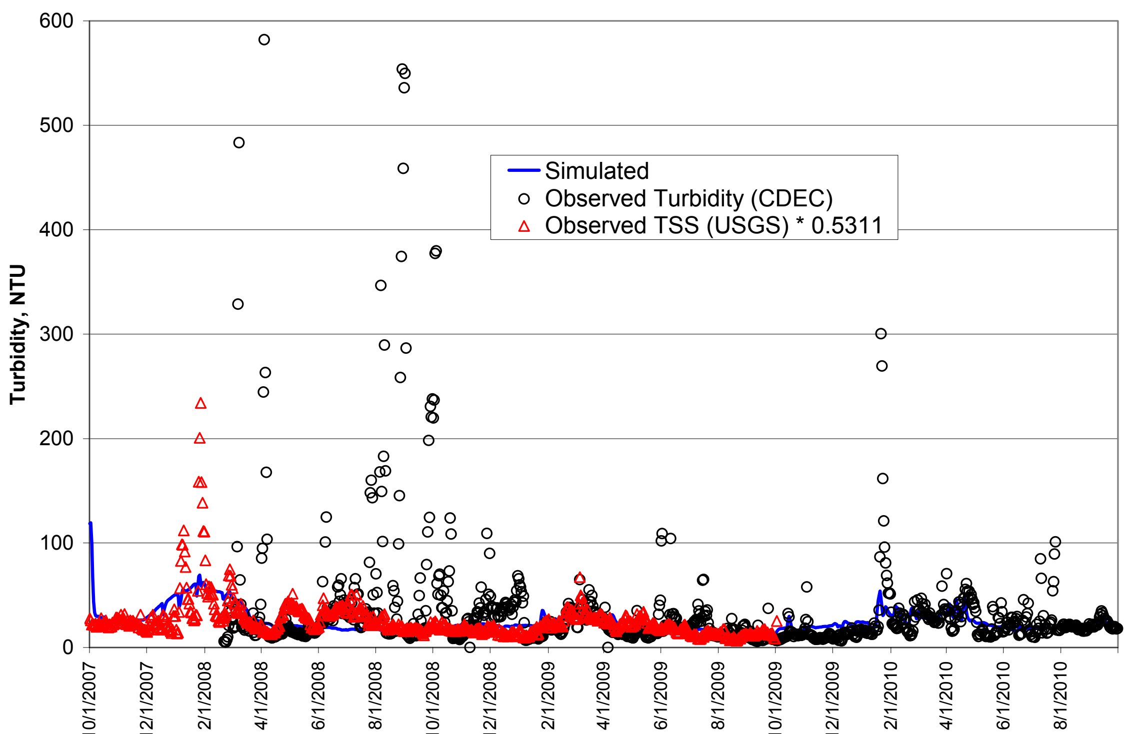

Figure 2-13 Simulated and observed Turbidity at San Joaquin River near Vernalis

Table 2.11 Turbidity Calibration Statistics for East Side Tributaries Locations

Turbidity Monitoring Station	Measured Time Period	% Relative Error	% Absolute Error	R squared
Cosumnes River at Michigan Bar	2002	19.5	38.4	0.668
Cosumnes River at Twin Cities Road	**1998-2006**	**-11.9**	**58.1**	**0.602**
Mokelumne River at Elliott	2000-2005	0.9	1.5	0.993
Mokelumne River at mouth	**2002-2010**	**-13.9**	**97.4**	**0.393**
Bear Creek near mouth	**2002-2007**	**13.5**	**164.0**	**0.00**
Calaveras River near mouth	**2008-2010**	**396.7**	**398.5**	**0.859**
French Camp Slough at Airport Way	**2006**	**-634.7**	**635.7**	**0.02**
San Joaquin River at Vernalis	**2008-2010 (CDEC)**	**-36.9***	**60.7***	**0.00***
San Joaquin River at Vernalis	**2007-2009 (USGS)**	**-1.5**	**36.0**	**0.27**

* Calibration statistics calculated as if continuous monitoring data were accurate

Organic Carbon

Differences between observed and simulated organic carbon were analyzed at six locations within the east side tributaries region of the Sacramento River WARMF model domain. These locations include Cosumnes River at Twin Cities Road, Bear Creek near mouth, Mokelumne River at mouth, Calaveras River upstream of Mormon Slough, Calaveras River near mouth, and French Camp Slough at Airport Way. Evaluating the simulation results at these locations lets us determine model performance in simulating organic carbon from different combinations of sources: upstream inflows, natural landscapes, agricultural areas, and urban areas.

Figure 2-14 through Figure 2-18 show the simulated and observed time series of total organic carbon at various stations within the east side tributaries region of the Sacramento River WARMF model domain. Each graph is focused on the time period between 2000 and 2010 for which there is observed data at each location. Generally, the WARMF simulation of organic carbon agrees well with the observed data, predicting peaks, troughs, and trends in concentrations. Rapid increases and/or decreases in TOC concentration can be seen in several of the figures. The sharp changes in concentration are generated by corresponding storm hydrographs. Depending on the magnitude and duration of a precipitation event, and the time between storms, organic carbon (and other chemical constituents) concentrations can change quickly. Concentrations will rise and fall sharply when overland flow occurs. The processes simulating buildup of organic carbon on the land surface and the amount of time between storms, which affects the amount of buildup, will determine whether concentrations increase or decrease when overland flow is contributing to the storm hydrograph. More subtle changes in stream chemistry are related to the variation in chemical concentrations in each of the soil layers and the relative contribution of flow from each layer.

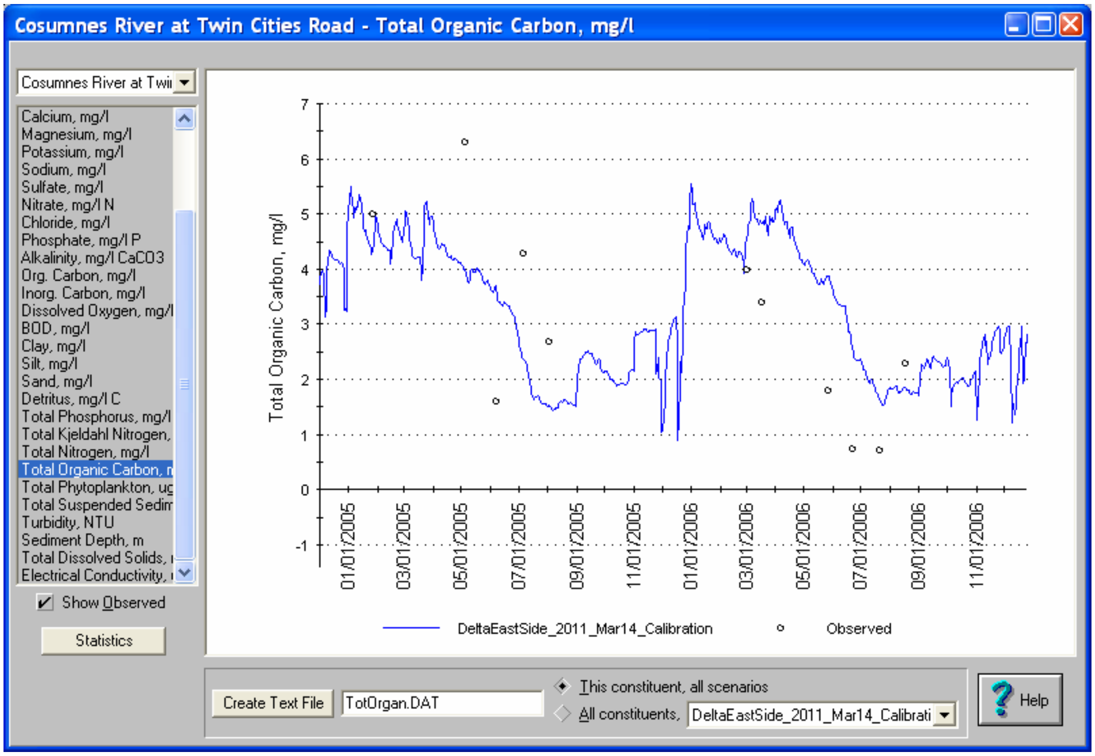

Figure 2-14 Simulated and observed total organic carbon at Cosumnes River at Twin Cities Road

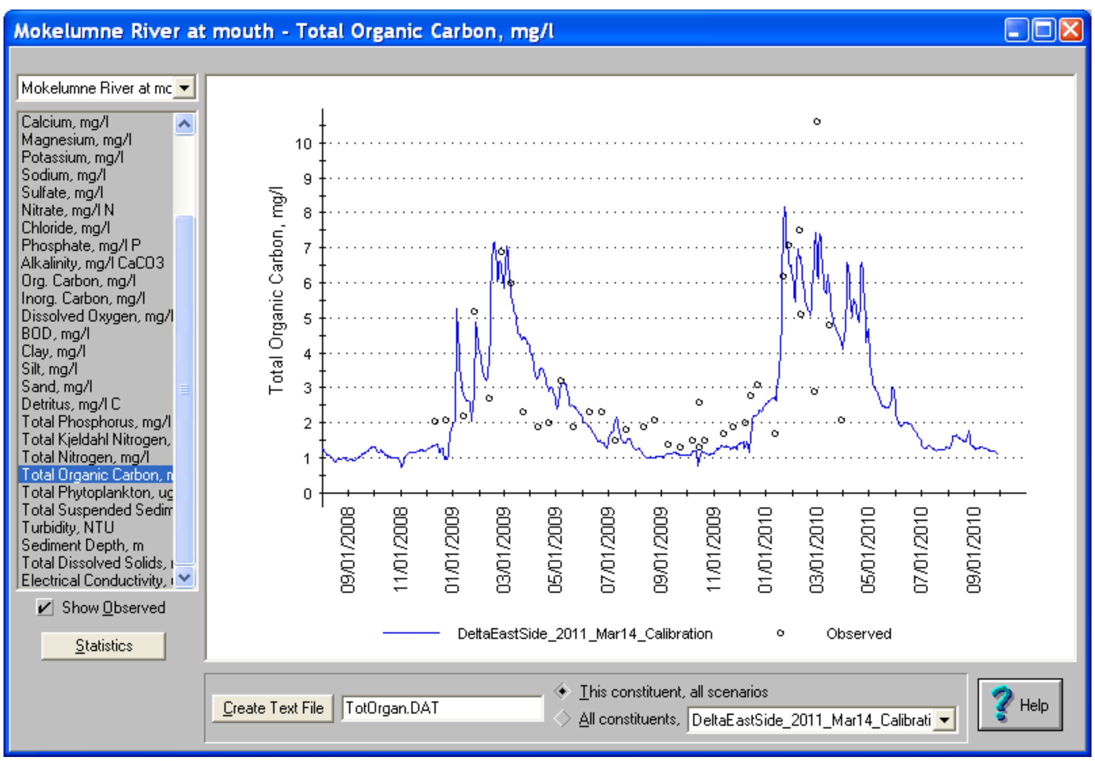

Figure 2-15 Simulated and total observed organic carbon at Mokelumne River at mouth

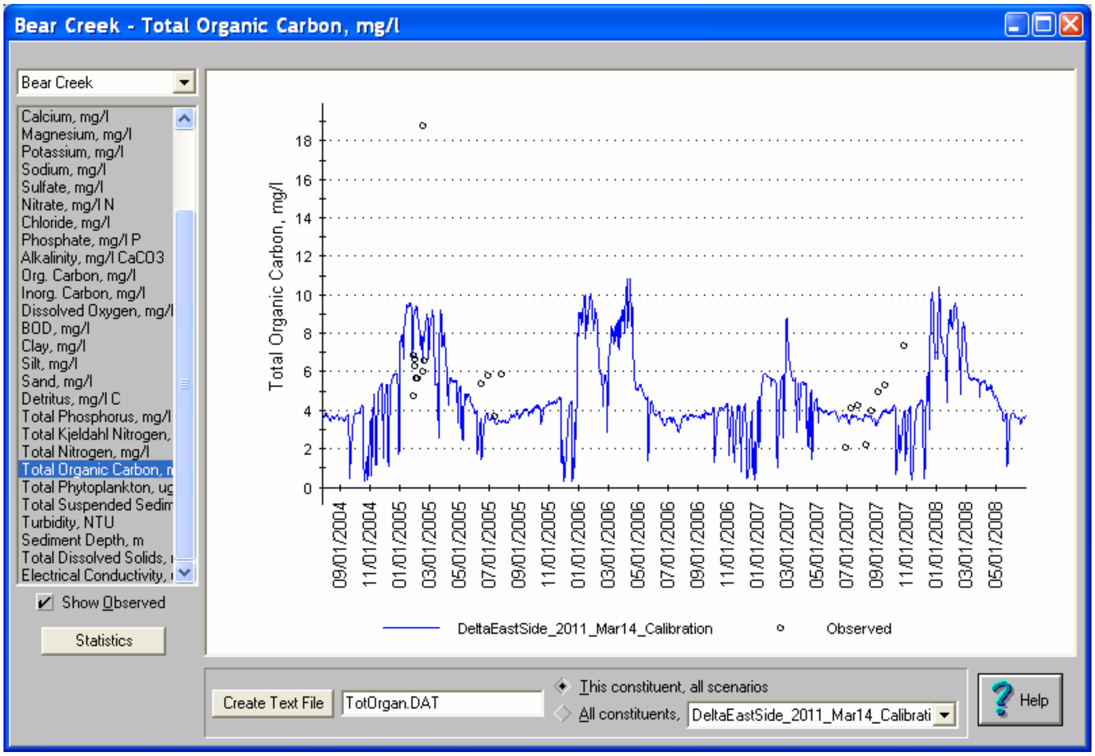

Figure 2-16 Simulated and observed total organic carbon at Bear Creek near mouth

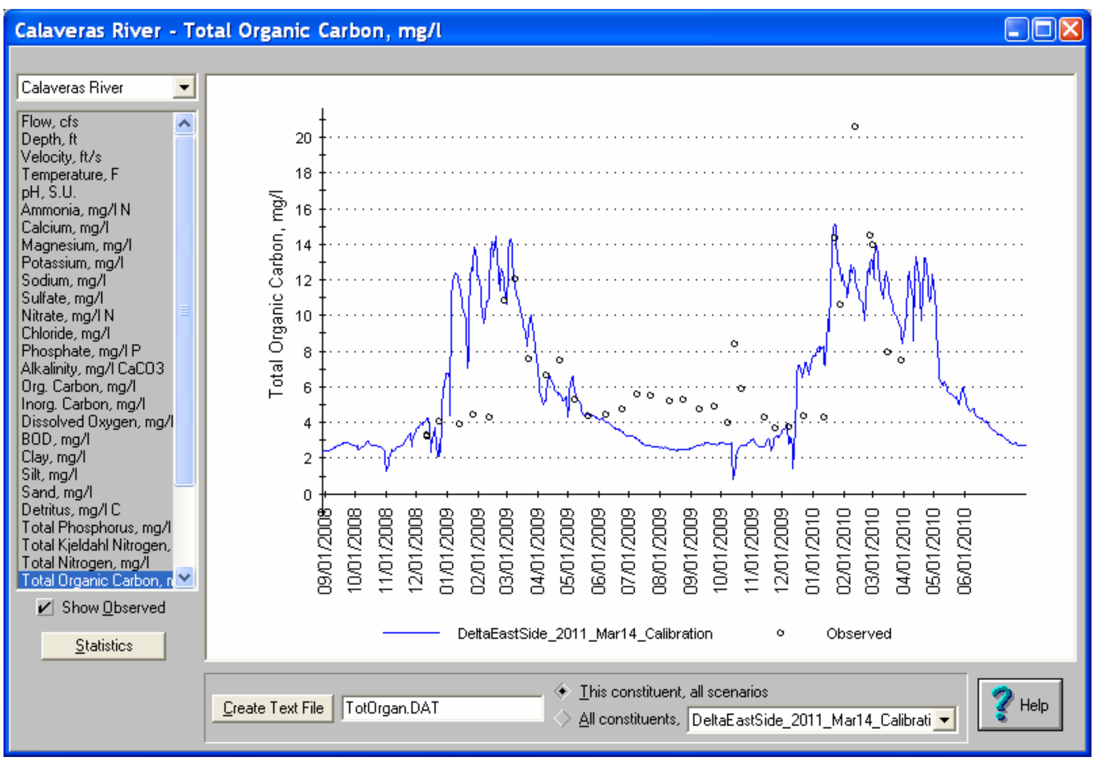

Figure 2-17 Simulated and observed total organic carbon at Calaveras River near mouth

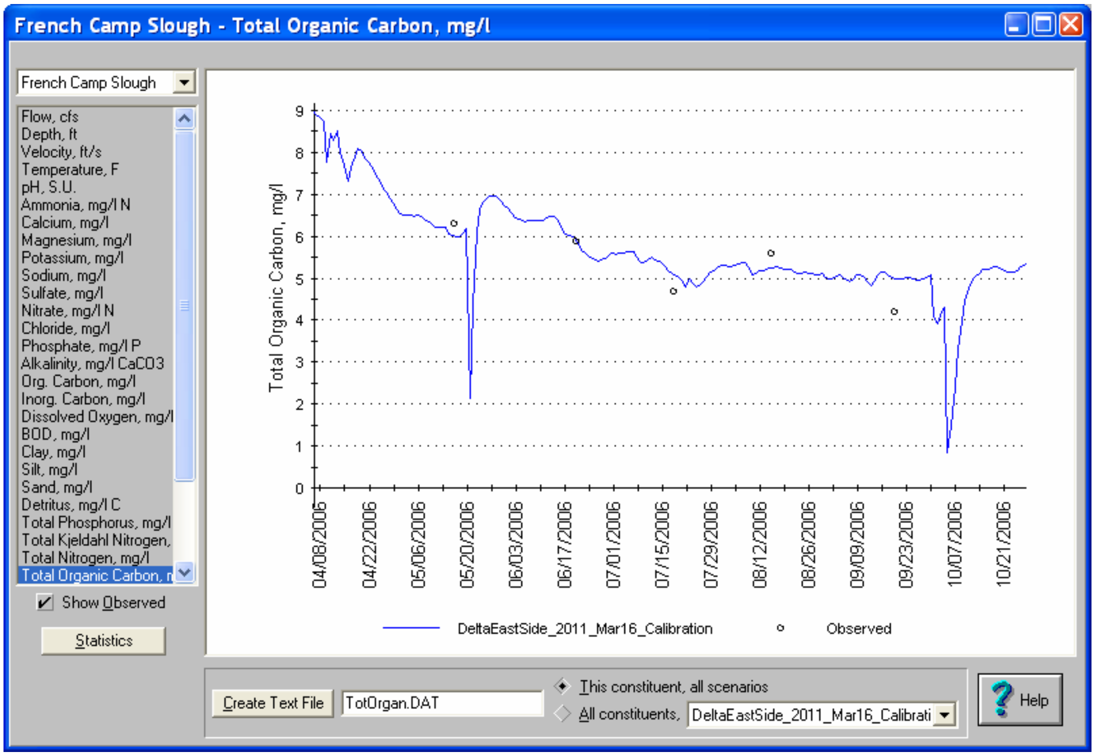

Figure 2-18 Simulated and observed total organic carbon at French Camp Slough at Airport Way

Table 2.12 shows the model errors for organic carbon the calibration locations within the east side tributaries region of the Sacramento River WARMF model domain. Loading of organic carbon to the Delta is of primary concern (as opposed to timing of organic carbon flux) to water resource managers due to the adverse effect that organic carbon has on standard drinking water treatment processes. Therefore, minimizing relative error was the primary focus of organic carbon calibration efforts. The relative error is within 10% at all of the stations selected for calibration.

Table 2.12 Total Organic Carbon Calibration Statistics for East Side Tributaries Locations

Organic Carbon Monitoring Station	Measured Time Period	% Relative Error	% Absolute Error	R squared
Cosumnes River at Twin Cities Road	2002	7.3	46.2	0.23
Mokelumne River at mouth	2009-2010	-1.8	40.8	0.67
Bear Creek near mouth	2005-2007	-6.2	48.3	0.10
Calaveras River near mouth	2008-2010	-3.8	60.2	0.42
French Camp Slough at Airport Way	2002-2006	2.6	7.5	0.80

The r-squared statistic is quite low for total organic carbon in the bear creek watershed. Figure 2-16 confirms that the simulation is not accurately predicting the timing of observed concentrations. Observed total organic carbon data collected at this location illustrate different patterns than those witnessed at the other observed data locations. Total organic carbon concentrations at this location do not appear to follow the seasonal pattern of high concentration during winter/spring months followed by relatively low concentrations during the summer/fall months. Unfortunately, the lack of stream discharge information, total organic carbon measurements and the inconsistency with which the organic carbon data were collected makes it difficult to assess whether there are different processes affecting organic carbon concentrations in Bear Creek or if the traditional processes dominate but are masked by an insufficient number of observed data points. Intrusion of Delta water with the incoming tide could be another source of model error. Therefore, there is a high degree of uncertainty associated with the estimates of organic carbon export from the Bear Creek watershed. Additional organic carbon data collection and the establishment of a stream discharge monitoring station within the watershed would be helpful in reducing the uncertainty associated with model predictions at all locations in general and in the Bear Creek watershed in particular.

Summary

This chapter summarizes the calibration of the Sacramento River WARMF model as of March 15, 2011. The primary goals of the modeling were to simulate stream discharge, turbidity and organic carbon flux to the Delta from the east side tributaries (Cosumnes, Mokelumne, and Calaveras Rivers) under present conditions and determine the upstream sources of these constituents. The comparisons of predicted and observed values were made over many locations, time periods, and seasons to demonstrate that the model can predict hydrology and the sources of turbidity and organic carbon between different land uses, regions, and hydrologic conditions. The model coefficients affecting stream discharge were calibrated to achieve a good fit at all locations where observed data are available. A summary of the final values for spatially-varying coefficients affecting stream hydrology is provided in Table 2.13.

The fit between simulated and observed turbidity were good in the Cosumnes, Dry Creek and Mokelumne, and Calaveras River systems. Simulated turbidity did not match the observed data as well in Bear Creek and French Camp Slough. These differences are likely the result of oversimplification of the calculation of turbidity in the model, possible intrusion of Delta water with the tides, and a general lack of sufficient stream discharge and turbidity data for calibration. The matches were good for organic carbon throughout the study area, with relative errors of less than 15% at all the locations used in the calibration. A summary of the final values for spatially-varying calibration coefficients affecting turbidity and organic carbon concentration is provided in Table 2.14. It is important to note that there are many additional coefficients that affect simulated stream concentrations of organic carbon, TSS and turbidity including the hydrology coefficients listed in Table 2.13, adsorption isotherms, soil particle size distribution, et cetera. Many of these parameters are also spatially variable, but are measured and therefore are considered to be model input (similar to precipitation data, watershed slope, etc.). The calibration conducted in the east side tributaries region of the Sacramento River WARMF model is sufficient to perform analysis of turbidity and organic carbon sources under current watershed conditions.

Table 2.13 Summary of Final Spatially-varying Hydrology Calibration Coefficients for East Side Tributaries Locations

Watershed	Soil Layer	Thickness (cm)	Initial Moisture	Field Capacity	Saturation Moisture	Horizontal Hydraulic Conductivity (cm/day)	Vertical Hydraulic Conductivity (cm/day)	Root Distribution
Camp Creek	1	40	0.3	0.4	0.5	8000	2000	0.8
	2	100	0.25	0.25	0.45	3000	1000	0.15
	3	100	0.2	0.22	0.35	200	500	0.05
Cosumnes River, Bear Creek	1	20	0.3	0.4	0.5	8000	500	0.8
	2	35	0.3	0.25	0.45	3000	200	0.2
	3	50	0.25	0.22	0.35	200	100	0
Dry Creek, Mokelumne River	1	10	0.1	0.4	0.5	12000	500	0.7
	2	20	0.1	0.25	0.45	8000	200	0.2
	3	70	0.1	0.22	0.35	200	100	0.1
Calaveras River, French Camp Slough	1	40	0.3	0.4	0.5	8000	500	0.8
	2	35	0.3	0.25	0.45	3000	200	0.2
	3	50	0.35	0.22	0.35	200	100	0

Table 2.14 Summary of Final Spatially-varying Water Quality Calibration Coefficients for East Side Tributaries Locations

Watershed	Soil Layer	Organic Carbon Calibration Parameters		Sediment / Turbidity Calibration Parameters		
		Initial Soil Dissolved Organic Carbon Concentration (mg/L)	Organic Carbon Decay Rate (1/day)	Soil Erosivity Factor	Percent Buffered (%)	Buffer Width (m)
Cosumnes River at Michigan Bar	1	6	0.01	0.07	97	10
	2	5				
	3	4				
Cosumnes River at mouth	1	6	0.01	0.32	15	5
	2	5				
	3	1				
Dry Creek	1	15	0.01	0.04	90	10
	2	12				
	3	10				
Mokelumne River	1	15	0.01	0.16	25	10
	2	12				
	3	10				
Bear Creek	1	9	0.01	0.28	0	0
	2	7				
	3	6				
Calaveras River	1	14	0.001	0.16	90	10
	2	12				
	3	11				
French Camp Slough	1	9	0.01	0.32	0	0
	2	8				
	3	7				

3 Source Contribution

Introduction

The stream discharge and water quality predictions discussed in Chapter 2 are useful for understanding patterns of flow and pollutant concentrations at specific points within the Sacramento River WARMF model domain. The calibration is also an important first step in understanding the reliability of the model to predict pollutant loads. The calibrated model provides information about source contributions of waters and pollutants, providing greater understanding of watershed system behaviors, which is important for the formulation of management alternatives.

Source of Water

Table 3.1 shows the average flows of source waters to the Delta, based on a simulation time period of 10/1/2000 through 9/30/2010. These locations include the Cosumnes River, Dry Creek, Mokelumne River, Bear Creek, Calaveras River, French Camp Slough, and local Delta drainages. During the simulation time period, average total inflow from upstream reservoirs is 724 cfs, which accounts for approximately half of the total flux of water from the east side tributaries region to the Delta. Camanche Reservoir on the Mokelumne River is the largest reservoir in the east side tributaries region, releasing a little more than three times the amount of water released from New Hogan Reservoir on the Calaveras River. The average quantity of water released from Camanche Reservoir is also larger than the flow entering the Delta from the Mokelumne River. The discrepancy is due to North San Joaquin Water Conservation District and Woodbridge Irrigation District diversions from the Mokelumne River. These two diversions account for average withdrawals of 28 and 87 cfs, respectively.

There are currently several other diversions included in the east side tributaries region that affect the water balance in the Cosumnes and Dry Creek watersheds. They include Eldorado Irrigation District withdrawals of a combined average of 40 cfs from Sly Park and Carson Creeks (Cosumnes River watershed), Omochumne-Hartnell Water District withdrawals of 72 cfs from Deer Creek and the Cosumnes River, Galt Irrigation District withdrawals of 14 cfs from Laguna Creek in the Cosumnes River watershed, and the Jackson Valley Irrigation District withdrawals of 14 cfs from Jackson Creek in the Dry Creek Watershed. Two point sources are currently included in the east side tributaries region of the Sacramento River WARMF model. The Galt Sewer District and the Sacramento Municipal Utility District contribute average flows of 3 and 18 cfs respectively. Evaporation from surface waters also accounts for a small amount of the difference between inflow and outflow within the model domain.

Table 3.1 Average Instantaneous Discharge of Source Waters to the Delta

Source	Discharge (cfs)	Percent of Total
Cosumnes River at mouth	547	35.2%
Dry Creek at mouth	153	9.8%
Mokelumne River at mouth	458	29.5%
Inflow from Camanche Reservoir	569	
Bear Creek at mouth	48	3.1%
Calaveras River at mouth	234	15.1%
Inflow from New Hogan Reservoir	155	
French Camp Slough at mouth	92	5.9%
Local Delta Drainage	22	1.4%

Since both inflows and diversions are seasonal, the relative amount of source waters varies monthly. Figure 3-1 shows the contributions of boundary inflows (Camanche and New Hogan Reservoir releases) and point sources (Galt Waste Water Treatment Facility and Sacramento Municipal Utilities District) to river outflow to the Delta. During the period between June and October, river outflow to the Delta is less than the boundary inflows. During these months water is diverted from the major rivers to irrigate agricultural lands within the east side tributaries watersheds. Much of this water is lost through evapo-transpiration processes (irrigation inefficiencies, crop plant respiration, etc.). Point sources are a very minor source of water in the east side tributary watersheds.

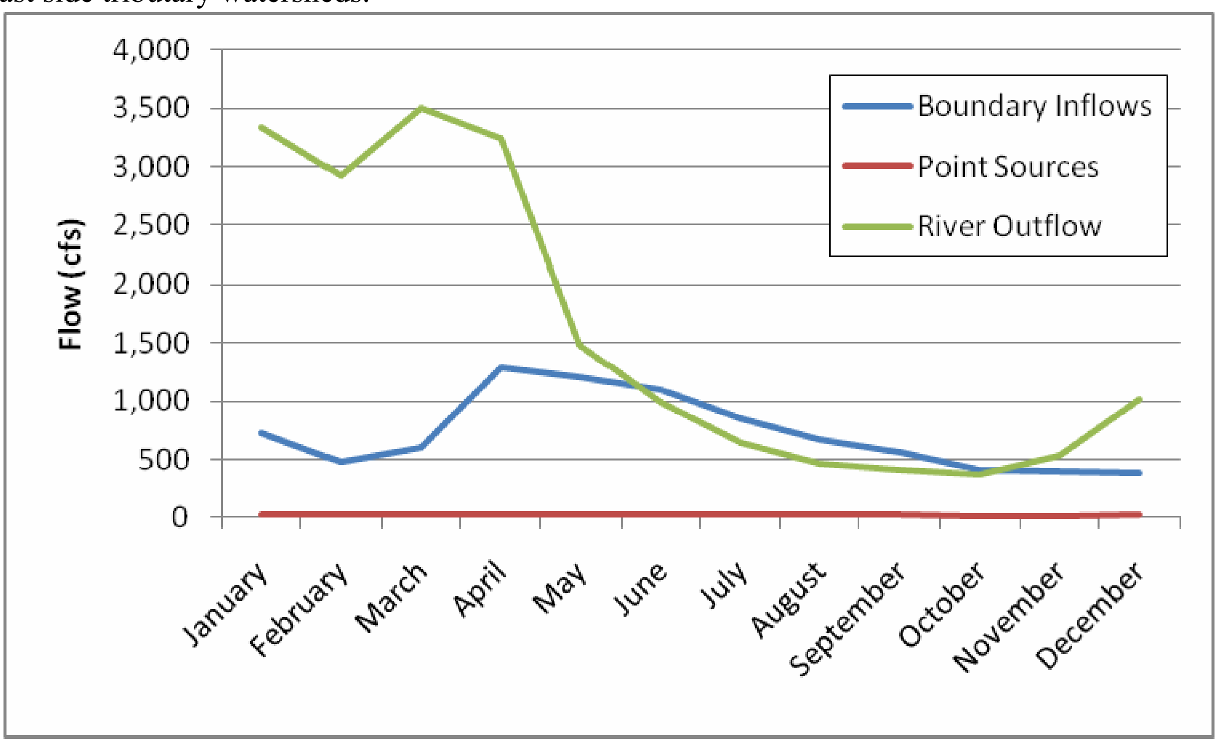

Figure 3-1 Average Monthly Source Waters of the Delta East Side Tributaries

Sources of Turbidity

Turbidity is calculated within WARMF as a linear function of clay and silt concentrations in the water column. Therefore, total suspended sediment (TSS) can be used to assess the relative contribution of turbidity to the Delta from the east side tributaries. Table 3.2 summarizes the sources of TSS load. Simulations indicate soil erosion from the land is the major contributor of TSS, and therefore turbidity to the Delta. Figure 3-2 illustrates that the majority of the non-point source sediment load is derived from natural land use classes. In the east side tributary watersheds, grassland/herbaceous and scrub/shrub land cover types produce over half of the sediment load to the Delta. A large portion of the sediment delivered to streams and rivers within the east side tributaries study area is predicted to settle out of the water column before reaching the Delta (Table 3.2). Approximately 85% of the sediment input is deposited in the stream channel. While the majority of this sediment is eventually scoured from the river bed and transported downstream, deposition is greater than resuspension in each of the major river systems within the study area during the 2000-2010 simulation timeframe. This indicates that sediment tends to aggrade in the lower parts of these river systems over time. Simulated sediment scour is dependent upon water surface slope and water depth. A detailed investigation of stream cross-section slope would be required to confirm the simulation results.

Table 3.2. Sources and Sinks of Total Suspended Sediment

Sources	Total Suspended Sediment Load (kg/day)						
	Cosumnes River	Dry Creek	Mokelumne River	Bear Creek	Calaveras River	French Camp Slough	Local Delta Drainage
Reservoir Inflows	**0**	**0**	**5,370**	**0**	**804**	**0**	**0**
Nonpoint Sources	**209,782**	**29,994**	**625**	**122,509**	**36,302**	**103,390**	**28,759**
Barren land	15,400	2	1	2,220	10,400	143	0
Deciduous Forest	937	154	0	87	78	186	10
Double Crop DLA	1,070	0	4	0	0	754	2,970
Evergreen Forest	7,820	2,200	0	19	119	130	0
Fallow	232	49	2	473	0	101	172
Farmsteads	4,500	5,560	1	1,440	920	224	75
Flowers and nursery	98	34	1	682	17	15	108
Grassland / Herbaceous	100,000	12,800	7	58,400	21,700	54,200	716
Mixed Forest	347	213	0	4	2	4	0
Olives, citrus & subtropicals	0	15	0	256	14	0	0
Orchard	408	59	7	1,610	83	1,880	1,400
Other CAFOs	870	0	1	2,230	0	834	47
Other row crops	1,960	25	9	2,040	12	9,420	4,540
Perennial forages	11,700	131	57	6,930	32	4,680	2,390
Rice	0	0	0	0	0	6,450	1,450
Shrub/Scrub	19,000	4,860	0	748	1,360	3,410	0
Urban Commercial	1,070	452	0	0	82	275	0
Urban Industrial	4,400	366	1	3,800	694	410	0
Urban residential	2,080	1,760	3	1,030	133	121	1,390
Vines	4,580	215	135	8,020	2	882	1,750
Warm season cereals/forages	27,600	641	299	29,300	280	7,170	6,090
Winter grains & safflower	5,710	459	98	3,220	373	12,100	5,650
Resuspension from River Bed	**75,723**	**35,879**	**4,366**	**11,454**	**22,004**	**13,912**	**550**
Point Sources	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Sinks							
Settling to River Bed	**199,891**	**46,262**	**4,576**	**96,446**	**37,166**	**67,259**	**4,831**
Diversions	**732**	**82**	**836**	**0**	**0**	**0**	**0**
NET DELTA LOAD	**84,882**	**19,529**	**4,949**	**37,517**	**21,944**	**50,043**	**24,478**
PERCENT CONTRIBUTION	**35%**	**8%**	**2%**	**15%**	**9%**	**21%**	**10%**

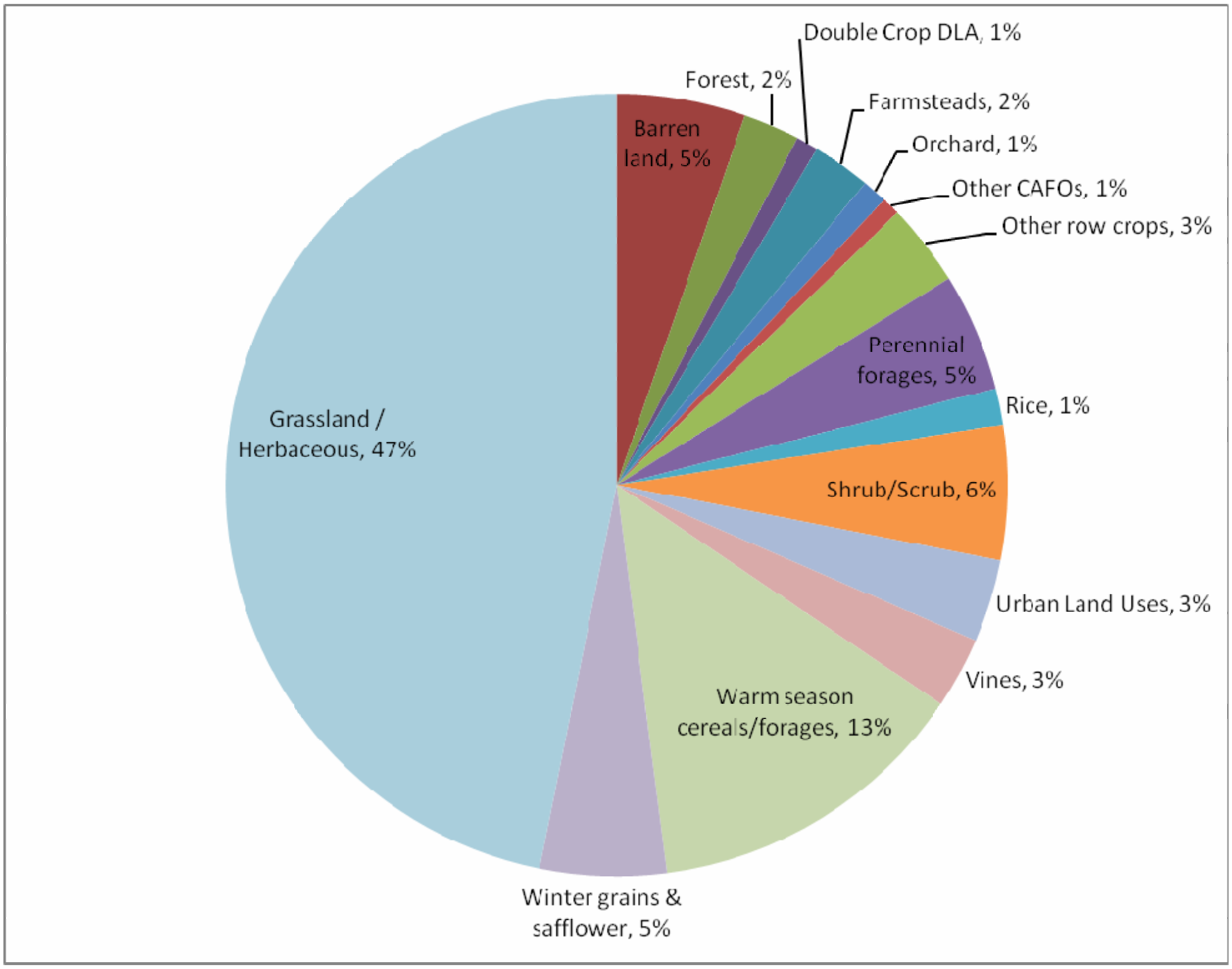

Figure 3-2 Non-point sources of total suspended sediment within the Delta east side tributaries region of the Sacramento River WARMF model domain

Figure 3-3 shows the relationship between TSS loading and concentration at the mouth of the Cosumnes River. This location was selected because it is the largest unregulated tributary to the Delta and contributes a larger percentage of the TSS load to the Delta than any of the other east side tributaries. The high proportion of TSS load generated in the Cosumnes River watershed (and therefore highest calculated turbidity values) is due to its unregulated flow pattern and lack of impoundments which trap sediment. Both concentration and load peaked each year during the high flow winter/spring runoff season. A secondary peak in concentration and load occurred in half of the years that were simulated. These peaks also occurred early in the year, and therefore were likely caused by precipitation in the east side tributaries region. Relatively little sediment was transported between the months of May and December, indicating that irrigation is not causing sediment mobility in the watershed. The simulated concentration varied between 5 and 15 mg/L during low flow time periods. Loading to the Delta was minimal during these time periods due to very small stream discharge quantity.

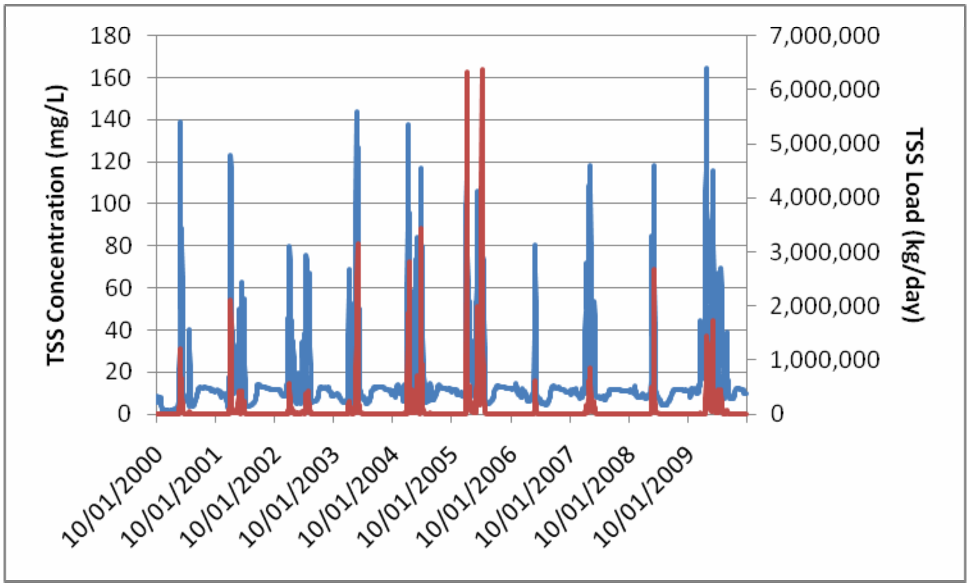

Figure 3-3 Total Suspended Sediment Load (red line) and Concentration (blue line) at the mouth of the Cosumnes River

Sources of Organic Carbon

Table 3.3 summarizes the sources of organic load to the Delta from the east side tributaries region of the Sacramento River WARMF model. The boundary river inflows from Camanche and New Hogan Reservoirs contributed about 12% of the load, while point sources contributed 4% of the total organic carbon loading. In-stream organic carbon production and resuspension of river bed sediment accounted for 17% of the load. Non-point source loading contributes the remaining 67% of the total organic carbon load to the Delta. The non-point source load is broken down by land use and graphically displayed in Figure 3-4.

Table 3.3 Sources and Sinks of Organic Carbon

Sources	Total Organic Carbon Load (kg/day)						
	Cosumnes River	**Dry Creek**	**Mokelumne River**	**Bear Creek**	**Calaveras River**	**French Camp Slough**	**Local Delta Drainage**
Reservoir Inflows	**0**	**0**	**2,220**	**0**	**1,270**	**0**	**0**
Nonpoint Sources	**9,072**	**4,367**	**94**	**1,156**	**2,514**	**1,882**	**281**
Barren land	64	0	0	5	36	1	0
Deciduous Forest	358	273	0	12	66	47	0
Double Crop DLA	23	0	1	0	0	9	1
Evergreen Forest	3,600	1,240	0	1	43	24	0
Fallow	22	8	2	7	9	4	5
Farmsteads	54	160	0	11	102	8	2
Flowers and nursery	1	1	0	4	2	3	1
Grassland / Herbaceous	3,000	1,610	7	689	1,420	979	4
Marsh	22	4	2	7	5	2	0
Mixed Forest	158	151	0	0	1	0	0
Olives, citrus & subtropicals	0	0	0	2	7	0	0
Orchard	16	9	5	25	327	92	47
Other CAFOs	8	1	0	5	2	2	0
Other row crops	26	9	1	22	104	126	37
Paved areas	2	1	0	0	0	0	0
Perennial forages	278	89	22	77	64	200	32
Rice	3	0	0	0	0	48	0
Sewage plant incl. ponds	1	1	0	1	2	0	0
Shrub/Scrub	771	415	0	9	110	56	0
Urban Commercial	3	11	0	0	2	1	0
Urban Industrial	22	13	0	11	8	2	0
Urban landscape	142	97	1	22	53	28	4
Urban residential	46	132	1	13	20	11	56
Vines	181	36	36	98	40	41	49
Warm season cereals / forages	187	56	11	107	40	76	25
Water	47	29	2	8	13	22	1
Winter grains & safflower	38	22	3	21	39	98	18
Resuspension from River Bed	**2,951**	**795**	**9**	**31**	**935**	**127**	**18**
Reaction Product	**1**	**0**	**79**	**0**	**1**	**0**	**0**
Point Sources	**662**	**645**	**0**	**0**	**0**	**0**	**0**
Sinks							
Settling to River Bed	**3,668**	**1,003**	**16**	**392**	**1,073**	**405**	**64**
Reaction Decay	**830**	**364**	**554**	**50**	**297**	**193**	**2**
Diversions	**432**	**41**	**266**	**0**	**0**	**0**	**0**
NET DELTA LOAD	**7,756**	**4,399**	**1,566**	**745**	**3,350**	**1,411**	**233**
PERCENT CONTRIBUTION	**40%**	**23%**	**8%**	**4%**	**17%**	**7%**	**1%**

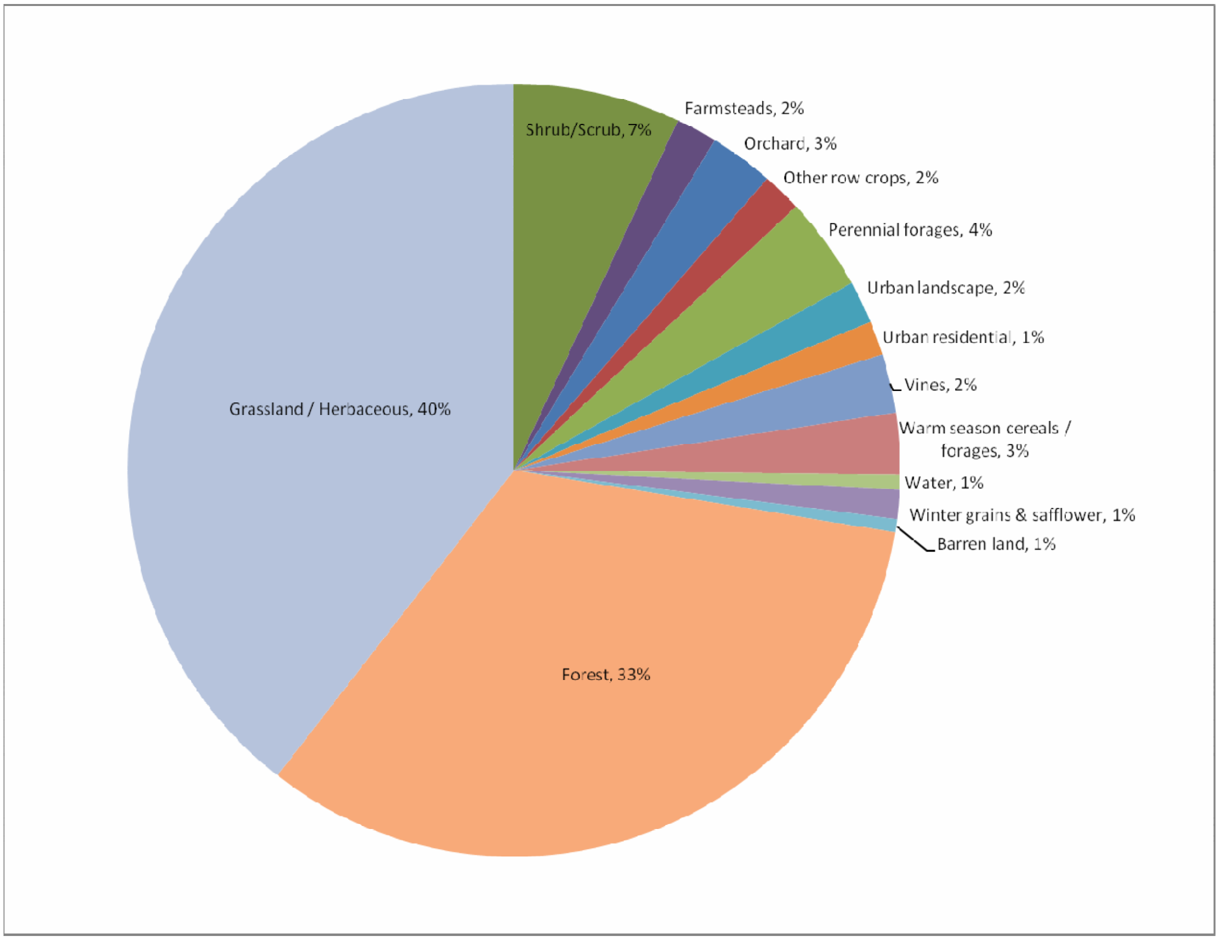

Figure 3-4 Non-point sources of total organic carbon within the Delta east side tributaries region of the Sacramento River WARMF model domain

Table 3.3 and Figure 3-4 show that the forest, grassland/herbaceous, and scrub/shrub land uses contribute considerably more nonpoint source load of organic carbon than other land uses combined. These three land uses contribute 80% of the non-point source load, and 54% of the total organic carbon load to the Delta from the east side tributaries.

An important management consideration is the intensity of loading, or the loading rate for a given land area. While the loading rate varies by catchment relative to meteorology, irrigation water quality, and catchment-specific reaction rates, average rates from the east side tributaries area are provided in Figure 3-5. Note that this breakdown is only for roughly two thirds of the overall organic carbon loading since it does not include inflows from reservoirs, in-stream production, resuspension, or point sources.

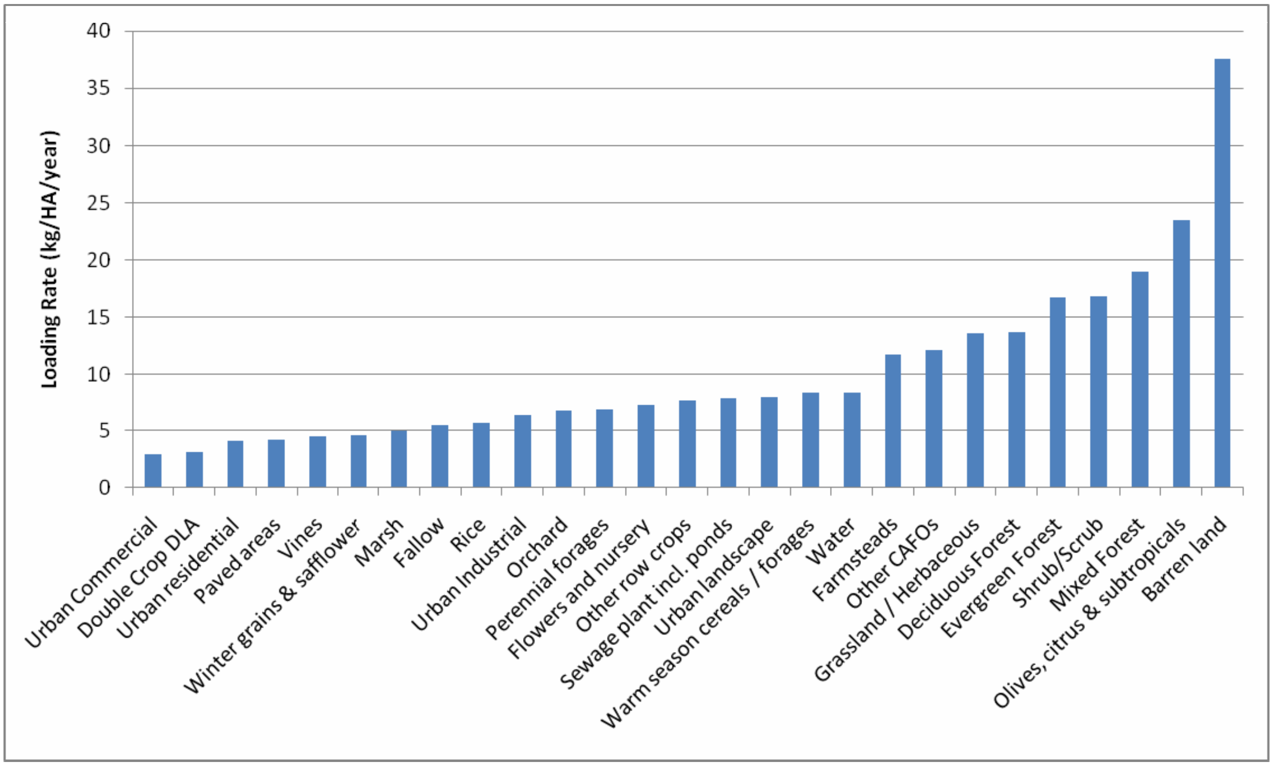

Figure 3-5 Organic Carbon Loading Rates by land use

Figure 3-6 shows the relationship between total organic carbon load and concentration at the mouth of the Cosumnes River. There were generally high concentration peaks twice a year: during the winter runoff season and during the summer irrigation season. The highest load of the year varied between the winter and summer peaks, depending on the quantity of precipitation received during the winter months. In years of high winter precipitation, the winter peak in total organic carbon load was larger than the summer peak which is dependent on irrigation water supply and usage.

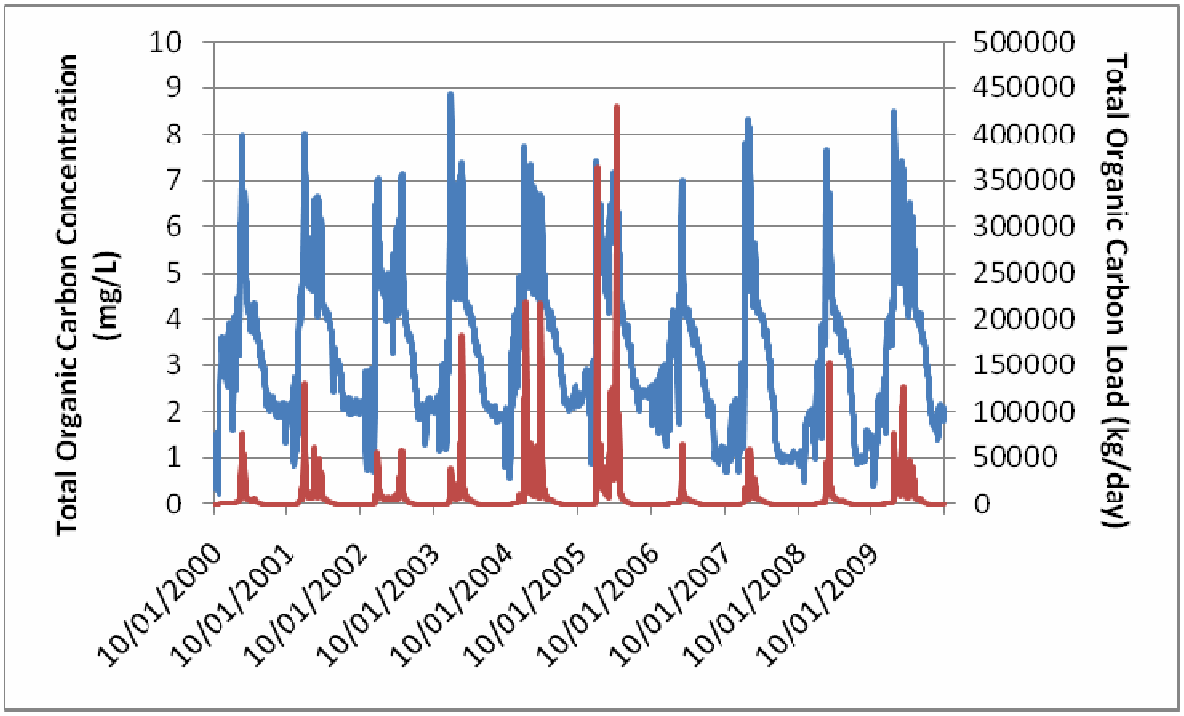

Figure 3-6 Total Organic Carbon Load (red line) and Concentration (blue line) at the mouth of the Cosumnes River

Management Implications

The applied WARMF watershed model can be used for short-term and long-term management of drinking water supplies. The long-term management of source watersheds is always important for maintaining high quality drinking water and minimizing treatment cost. The results of the source contribution analysis have implications for the management of the east side tributaries watersheds. The sources of pollutants were identified along with the loading from each source. Combined with calculations of Delta loading from the Sacramento and San Joaquin watersheds performed for other projects, the simulation of the east side watersheds completes the accounting of pollutant loading entering the Delta from upstream watersheds. This gives an indication of where long-term reduction strategies should be focused.

Short-term management involves changing the operation of the pumps at the drinking water intakes to maintain the desired water quality. This requires use of WARMF and the Delta DSM2 model in forecasting mode. Simulations of Delta water quality are sensitive to the flow and water quality inputs to the Delta. The Delta east side tributaries are not well monitored in real-time and monitoring regardless cannot predict future water quality. The WARMF model has demonstrated an ability to simulate historical flow and water quality including predictions of the timing of peak flow and loading. Given predicted meteorology and reservoir releases, the calibrated model can be used to project short-term future flows and loadings to the Delta. These can be used as inputs to the Delta DSM2 model to improve its predictions of water quality at the drinking water intakes.

There are various potential causes of future change to the water quality entering the Delta including changing land use, changing climate, reservoir management, agricultural practice, or water quality improvement strategies. In reality, a combination of these changes will occur. The calibrated model can be used to understand how these changes will affect water quality entering the Delta. The model can use projected conditions as input to determine how loading might change from the present baseline.

Land Use

Table 3.2 and Table 3.3 show the nonpoint source loading of total suspended sediment and total organic carbon coming from various land uses. As land use changes in the future, a quick assessment can be made on the likely impact by comparing the intensity of loading from the land use types which are increasing compared to the types which will be replaced. Specific local conditions can affect loading, however. The new land uses can be entered into WARMF to run a simulation comparing the projected future conditions against the past to determine the impact. Land use changes can affect not just average loading as shown in the summary tables but also the magnitude of peak concentrations, which could have implications for short-term management of the pumps at the drinking water intakes.

Reservoir Management

Table 3.2 and Table 3.3 show that the boundary inflows are the source of substantial loading of total suspended sediment and total organic carbon to the Mokelumne and Calaveras Rivers. With changes in land use, irrigation patterns, climate, and environmental restrictions the timing and magnitude of reservoir releases may change in the future. A short or long term decrease in reservoir releases would increase the proportions of the various sources of pollutants in the watershed including agriculture, point sources, and urban areas. Projections of reservoir releases from the CALSIM model or other sources can be used as WARMF inputs to determine the impact upon concentration and loading to the Delta.

Agricultural Practice

The crops grown in the east side tributary watersheds respond to changes in market demand and water supply. Each crop can have a different impact upon the water quality thanks to changes in irrigation water usage, fertilizer application, and productivity. Economic or environmental constraints may change how current crops are farmed, resulting in more efficient irrigation methods or reduced fertilizer usage. These changes can be simulated in WARMF to determine how these changes might affect water quality downstream.

Water Quality Improvement Strategies

Reducing nonpoint source loading under the existing land use configuration is a desirable approach to improving water quality. The source assessment using the calibrated WARMF model shows that point sources produce a minor percentage of the total suspended sediment and total organic carbon loading. Best management practices such as the use of detention ponds to capture storm runoff and buffer strips to capture sediment and adsorbed pollutants can reduce nonpoint source loading. The WARMF model can simulate these changes to guide decision makers on the most effective pollution control methods to use given limited funds for implementation.

4 CONCLUSIONS AND RECOMMENDATIONS

An existing WARMF model of the Sacramento River was extended to include the geographic region between Morrison Creek and the Stanislaus River. This area, referred to as the east side tributaries, includes the Cosumnes, Mokelumne, and Calaveras rivers, Dry Creek, Bear Creek, French Camp Slough, and land area draining directly to the Sacramento – San Joaquin river Delta. Data was collected for the east side tributaries back to October 1, 1921 to coincide with the existing Sacramento River WARMF model timeframe and facilitate linking to the CALSIM model. There was sufficient data to provide model inputs and to judge the calibration of model outputs. Measured flow and water quality from many historical time periods were used to calibrate the model. Calibration proceeded from upstream to downstream, prioritizing the DSM2 model boundary control points. This was done because the primary consideration for management of Delta drinking water facilities is the timing of flow and loading to the Delta. The calibration strategy included sufficient resolution to identify the sources of pollutants within regions and land uses in the watershed.

The calibration of the WARMF model showed good results for flow, total suspended sediment (which is used within WARMF to calculate turbidity), and total organic carbon. Flow calibration is very strong for the Cosumnes and Mokelumne Rivers, and Dry Creek. Observed stream discharge data are not available for the Calaveras River or French Camp Slough so calibration of simulated discharge was not possible in these watersheds. The relative error of simulated turbidity was less than 15% at the downstream-most monitoring location on the Cosumnes and Mokelumne River systems. Model performance statistics were generally poor for turbidity in the Calaveras River, Bear Creek, and French Camp Slough watersheds. In the case of the Calaveras River, it appears that the model is simulating the timing and magnitude of turbidity flux relatively well and the majority of error is related to predictions during the low flow time periods. The reasons for poor model performance in Bear Creek and French Camp Slough are more difficult to ascertain. Neither of these watersheds has an observed stream discharge monitoring station so there is a high level of uncertainty associated with the simulated stream discharge. Additionally, the quantity and consistency of water quality samples are not sufficient to determine whether the errors are due to the model coefficients that affect sediment transport, oversimplification of the turbidity calculation routines, tidal infiltration, or poor hydrology simulation performance. The model simulations showed relative error under 10% for organic carbon at each of the east side tributaries monitoring locations.

The sources of pollutants were analyzed with the calibrated model. The two major sources of total suspended sediment were inflows from upstream reservoirs and nonpoint sources. The majority of the nonpoint source load of total suspended sediment came from natural land covers. The largest source of total organic carbon load was nonpoint sources in the unregulated watersheds and reservoir inflows in the Mokelumne and Calaveras River watersheds. A breakdown of the non-point source organic carbon load suggests that forests, grasslands, and scrub/shrub contributed the vast majority of the non-point source load in the east side tributaries.

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